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October 1986

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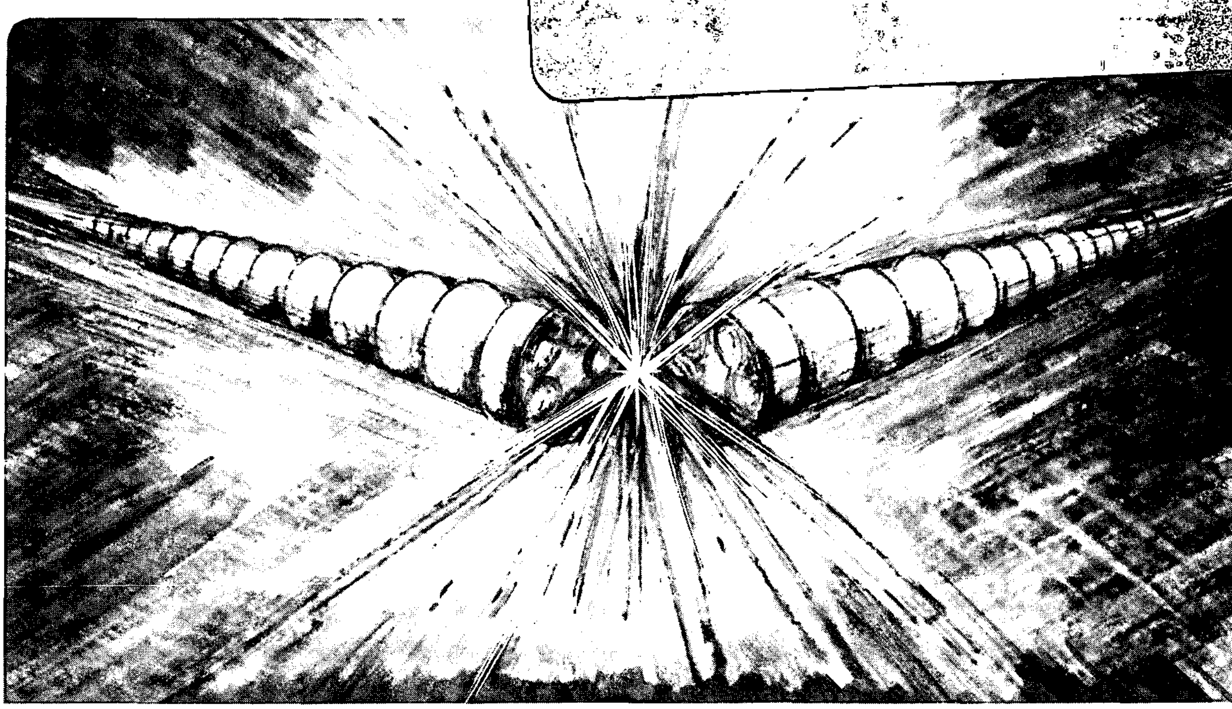

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PROSPECTS FOR FUSION POWER*

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PROSPECTS FOR FUSION POWER*†

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Introduction

The heavy ion fusion accelerator research (HIFAR) program at Berkeley is addressing the question of using beams of very heavy ions ($A \approx 200$) to drive inertial confinement fusion. Thus we are focussed on just the driver development and, for inertial fusion to become practicable, we must rely on successful solutions to the capsule physics, target fabrication and reactor design coming from work at other laboratories.

In September 1982, in an article in Physics Today, John Nuckolls was brave enough to make up a score-card for the various driver candidates then under consideration (see Fig. 1). He rated each in light of its ability to meet several key requirements, e.g., irradiance, target coupling, efficiency (10-20%), repetition rate (10-20 Hz), and cost (he felt $200/joule to be a viable economic figure). Nuckolls entered a "plus" where he felt that the requirement had been or was likely to be met. As you can see the heavy ion driver scored highest at that time. The concept was rather solidly based on existing accelerator technology in many respects such as reliability, repetition rate, efficiency, and the classical energy deposition of heavy ions. But it required an extrapolation to beam currents of much higher value than usual in research accelerators and, in addition, required that excellent optical quality (low emittance) be maintained through all stages of acceleration.

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Since then there have been three very encouraging developments. We have completed an important experiment to explore the beam-current limits for low energy heavy ions in a long focussing channel made up of many quadrupole lenses. Both the experiment and simulations agree that the current that can be sustained in a vacuum transport system without degradation of quality can be greater than dreamt possible just a few years ago. This result allows us to contemplate the beneficial use of ions with charge-state greater than unity, which had been our conservative choice early on because of fear of space-charge problems.

Secondly, we are half-way through building a proof-of-principle, multi-gap, induction accelerator experiment to establish how well we can accomplish, simultaneously, three novel accelerator strategies -- acceleration of heavy ions by linear induction, handling separately-focussed multiple beams in the same accelerator, and beam current amplification during acceleration.

Thirdly, we have had an intensive systems assessment underway for the past year and a half to examine power plant designs based on an induction linac driver. This study is nearing completion and suggests that the driver cost for a 1 GWe plant might lie below $200/joule.

2. Heavy-Ion Accelerator Requirements

For inertial fusion driven by particle beams the range of the ions should be approximately 0.1 - 0.2 gm/cm^2. If the ions are light (protons-lithium) the kinetic energy is low and can be supplied by the 10 MV technology pioneered at Sandia, Albuquerque. For heavy ions (mass number 200, say) the kinetic energy needed is very much larger -- 10 GeV -- and the technology of multigap accelerators is needed. For these, a considerable base of experience exists in the fields of high-energy and nuclear physics; hence the performance of such systems, e.g., reliability, long life, high repetition rate, is rather well established. Thus the downstream engineering problems of moving from fusion demonstration to fusion commercialization can be enormously simplified. Contributing to the reliability, in particular, is the reliance on multigap technology for which the accelerating energy is stored in many small packages. Also, the ions are focussed in vacuum and, unlike a laser beam, do not impinge on material lenses or mirrors. The electrical efficiency of a driver can be calculated quite well and recent studies show values of 30% and more are practicable.

The induction linac approach is well suited for very high currents and short pulses, and driving the high-currents needed for inertial fusion poses no problem (beam currents higher than needed have been routinely produced in electron induction linacs). The snag lies in our inability to focus and transport the high current beams, especially at low velocity where the space-charge defocussing self-fields are very large. Thus an essential ingredient of the induction linac strategy is to start out with quite a low current in the beam-pulse from the injector, say 10 amps, and to amplify the current as we accelerate in a way that keeps pace with the kinematical increase of the space-charge limiting current with velocity. Thus at the exit of the accelerator, at 10 GeV, the current can be several kiloamperes. Correspondingly, the pulse duration at the beginning will be many microsecond in duration and will shorten to one-tenth of a microsecond at the end. After exiting the accelerator the bunch can be shortened further in time -- to 10 nsec -- by arranging for bunching to occur in the final beam transport lines to the target.

Figure 2 shows the partially assembled apparatus for a proof-of-principle experiment, MBE-4, at Berkeley as of April, 1986. Four high-current cesium ion beams are generated in the 200 kV injector seen at the left and are transported in separate sets of quadrupole lenses. Eight induction accelerating units can be seen in place; each contains a number of ferromagnetic transformer cores; when completed MBE-4 will have a total of twenty-four accelerating units. The accelerating voltages produced by these units are tailored to bring about the current-amplification maneuver.

Beam-current profiles for all four beams shown in Figure 3 show the beam pulses at injection and after some acceleration. It can be seen that the current amplitude is, indeed, being increased and the pulse-duration correspondingly decreased. Extensive measurements will be needed to determine how well the optical quality of the beams is preserved; it is still too early to say.

The Heavy Ion Fusion Systems Assessment study currently nearing completion is a collaborative effort by McDonnell-Douglas, Los Alamos, Livermore, Berkeley, Wisconsin, ETEC, Titan, and SLAC. The examination of power plant options ranged over five different target designs, four different reactor concepts and a whole host of induction linac designs (different energies, number of beams, ion species, repetition rates, etc.) The driver designs took advantage of the new experimental and theoretical understanding of high-current beam transport limits, and the study concluded that the driver cost could be significantly reduced by using heavy ions with charge-state, $q = 3$, rather than the singly-charged ions preferred in the past. For a plant size of 1 GWe the cost of electricity turns out to be slightly less than that obtained in the STARFIRE and MARS fusion studies. Finally, a particularly interesting conclusion is that the cost of electricity remains very close to the optimum value -- within 5% -- over a very broad range in the choice of the accelerator parameters, such as kinetic energy, repetition rate, etc. Preliminary results and more details will be given at the Heavy Ion Fusion Symposium to be held in Washington, D.C. in May 1986.

Figure Captions

Figure 1: A score-sheet for fusion driver candidates due to J. Nuckolls.

Figure 2: Part of a proof-of-principle experiment on the induction acceleration of multiple beams of heavy ions with beam current amplification. Eight of the planned twenty-four accelerating units are in place. The four-beam cesium injector is at the left.

Figure 3: Initial results on beam current amplification for each of the four cesium ion beams. The lower traces show the injected beam pulse; the upper traces are after some acceleration and show how the current is increased and the pulse length shortened.

Driver Candidates

Requirements	CO_2 laser	KrF laser	Free electron laser	Heavy-ion accelerator	Light-ion accelerator
Efficiency (10–20%)	?	?	+	++	+
Focusing (10^{14}–10^{15} W/cm^2 at 5m)	+	+	+	+	?
Target coupling (10%)	?	++	++	++	+
Repetition rate (10–20 Hz)	+	+	++	++	+
Cost ($200/joule at 2 MJ)	+	+	+	+	++

+ : meets requirements.

Figure 1

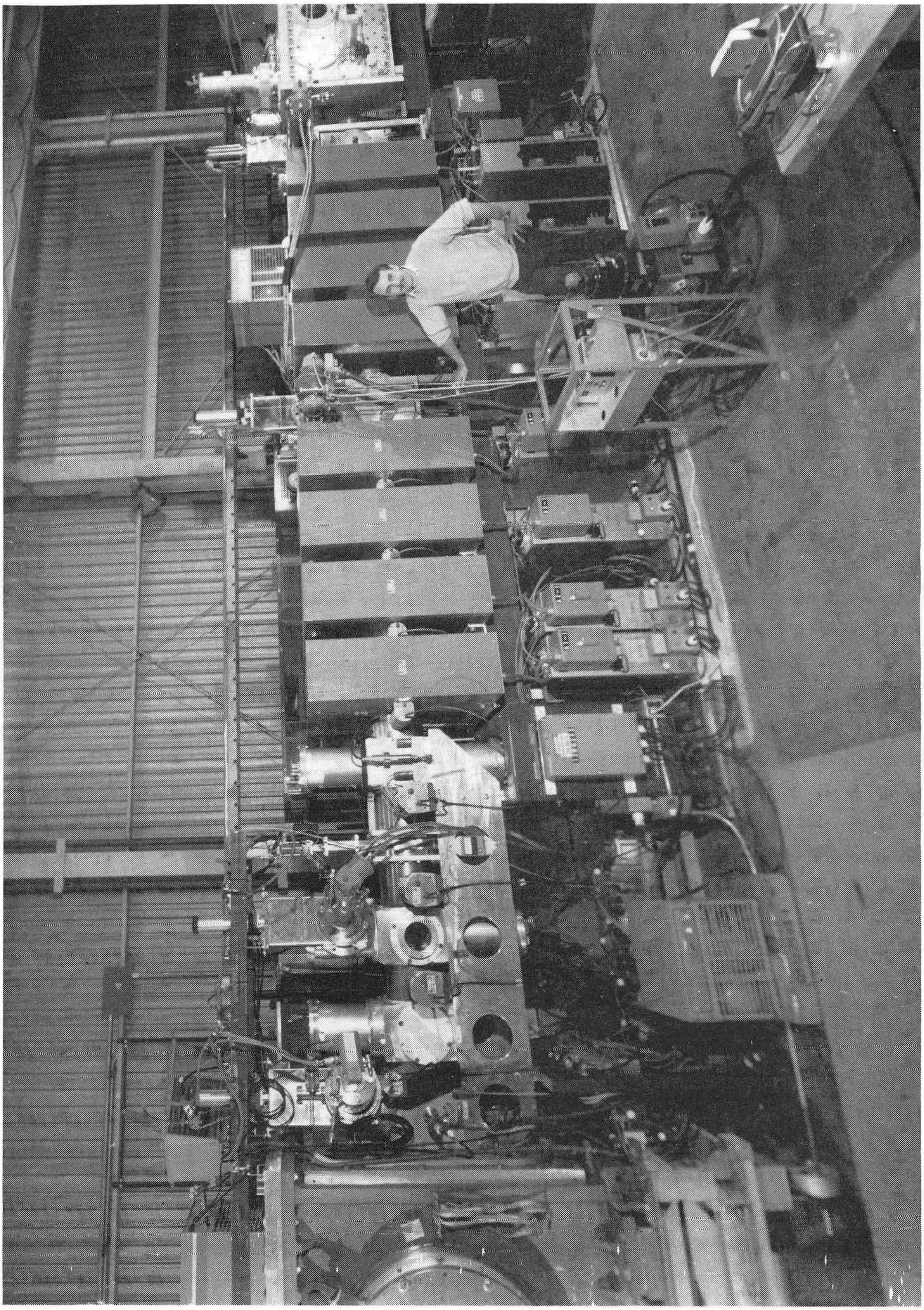

Figure 2

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MULTIPLE BEAM EXPERIMENT (SEC. B)

Cesium Beams, 10–Shot Overlays, 0.2 Hz.

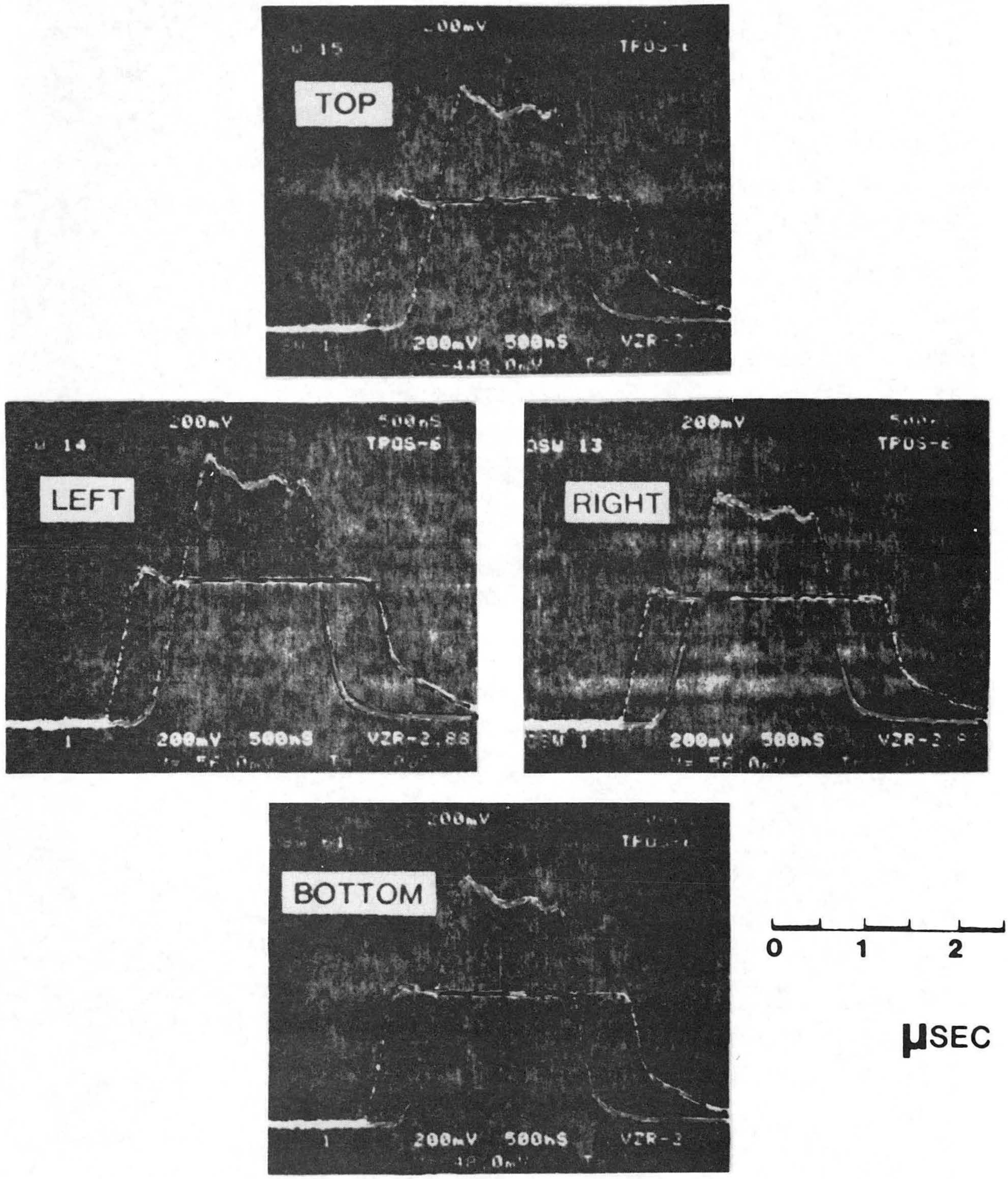

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Figure 3

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