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ACCELERATORS FOR HEAVY ION INERTIAL FUSION: PROGRESS AND PLANS*

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Abstract

The Heavy Ion Inertial Fusion Program is the principal part of the Inertial Fusion Energy Program in the Office of Fusion Energy of the U.S. Department of Energy. The emphasis of the Heavy Ion Program is the development of accelerators for fusion power production. Target physics research and some elements of fusion chamber development are supported in the much larger Inertial Confinement Fusion Program, a dual purpose (defense and energy) program in the Defense Programs part of the Department of Energy. The accelerator research program will establish feasibility through a sequence of scaled experiments that will demonstrate key physics and engineering issues at low cost compared to other fusion programs. This paper discusses progress in the accelerator program and outlines how the planned research will address the key economic issues of inertial fusion energy.

1. INTRODUCTION

The realization of hopes that thermonuclear fusion will fulfill the energy requirements for a future when fossil fuels are no longer viable depends on finding solutions to two issues: (1) economically and environmentally attractive energy from mature power plants, and (2) an affordable research program leading to this goal. Arguably, the affordable research program is the more important issue at the present time. Section 2 describes a research program leading to a heavy-ion fusion power plant. Section 3 discusses the long-term cost of electricity and Section 4 describes current research.

2. RESEARCH PROGRAM

Figure 1 shows a research plan leading to a demonstration power plant. This plan assumes that the important target physics issues will be addressed on the proposed National

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Ignition Facility (NIF) described elsewhere in these proceedings. The driver for the NIF will be a glass laser. It will not have the pulse rate, the efficiency, nor the durability required for power production. Therefore, the U.S. Department of Energy is developing heavy-ion accelerators as drivers. Large accelerators for high energy physics have high pulse rates, good reliability, and long life. We believe that heavy-ion accelerators for fusion can have these same characteristics and also high efficiency. The new feature needed for fusion is high peak beam power (greater than 100 TW) This power must be achieved while retaining the beam quality (low emittance) needed to focus the beams onto a small target. Theory, simulation, and several small experiments show that high peak power is achievable, but definitive validation requires experimentation with driver-scale beams. The Induction Linac Systems Experiments (ILSE) program shown in Fig. 1 will provide driver-scale beams. The combination of the NIF and ILSE results will, in about 2005, provide the basis for designing and building an accelerator that can be upgraded to drive a demonstration power plant. In heavy-ion fusion, the accelerator (the heating system) is roughly the analog of the ohmic, RF, and beam heating systems of a tokamak. The fact that a single, expandable driver can be used for the scientific, engineering, and demonstration phases of the program leads to relatively low research costs.

There are also other reasons why the research program will be relatively inexpensive. The size of the target chamber is only weakly related to confinement; the reactions take place in less than a cubic millimeter. Furthermore, the target energy yield and the time-averaged fusion power can be varied over a wide range by varying the beam energy, the mass of the fuel, the composition of the fuel, and the pulse rate. Therefore, target-chamber research on wall protection, tritium breeding, etc., can be done at small scale. Accelerators consist of many identical or similar components. This modularity minimizes development costs. Finally, many target chamber designs use fluid wall-protection that attenuates the neutrons sufficiently that existing stainless steels can be used as low-activation wall materials. Considering the aforementioned characteristics, we estimate that the cost of developing heavy ion fusion is much less than the cost of developing magnetic fusion. Because the accelerator itself accounts for roughly half the cost, the accuracy of this claim depends strongly on the accuracy of the accelerator cost estimates. In this regard, it is noteworthy that several accelerators of the scale required for fusion have already been built, e.g., at SLAC and Fermilab in the U.S. and at CERN, DESY, Protvino, and KEK in other countries.

3. LONG-TERM ECONOMICS

Recent studies [1-3] show that the long-term cost of electricity for heavy ion fusion power plants compares favorably with the projected cost of electricity from tokamaks [4] and other sources [5]. Nevertheless, since the accelerator is expected to be the most expensive component of a power plant, accelerator cost reduction is desirable. It is, of course, also desirable from the standpoint of research costs.

Induction accelerators are the principal approach to heavy-ion fusion in the U.S. An induction linac consists of a sequence of toroidal ferromagnetic cores surrounding the beam. The cores are pulsed sequentially as the beam or beams pass through them. The amount, and therefore cost, of ferromagnetic material depends on the pulse length and voltage, but not on the beam current. Reducing voltage (ion energy) while increasing current to meet the power requirement is generally an effective way to reduce cost. Because the repulsive space charge forces make it difficult to focus unneutralized beams if the ion energy is much less than 10 GeV, it would be desirable to develop focusing methods of the beams that employ charge neutralization. The important question is: Does neutralization destroy the beam quality so the ions cannot be focused onto a small target? A second approach to cost reduction is

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recirculation. It may be possible to reduce size and cost by passing the beam through the same accelerating structure 2 to 100 times. Recirculation is common in accelerators for particle physics, but fusion accelerators must carry larger currents. Analysis and numerical simulation of both methods of cost reduction are encouraging, but large-scale experiments are needed.

4. EXPERIMENTS

The main experimental activity in the program is the design of the ILSE accelerator, shown schematically in Fig. 2. It consists of a four-beam, 2 MeV injector, an accelerator section employing electrostatic focusing lenses, and an accelerator section employing magnetic focusing lenses. The electrostatic section accelerates four beams from 2 MeV to 5 MeV. At this point the four beams are combined transversely into a single beam that is then accelerated to 10 MeV in the magnetic section. Beam combining is a promising way to increase beam current and reduce cost. The ILSE beams will be driver-scale in diameter and charge per unit length. The main differences between ILSE and a driver are in number of beams, ion kinetic energy, and pulse length. To minimize ILSE cost these parameters are only large enough to address the important physics issues. The ILSE experimental area is large enough to accommodate a large ring for recirculation studies. ILSE will enable us to study current limits, neutralization, and recirculation. According to present Department of Energy plans, the electrostatic section will be built before the magnetic section. The electrostatic section alone is referred to as Elise.

We have made substantial progress toward ILSE. A single-beam, 2 MeV injector is currently in operation at Berkeley. The Berkeley team is also currently assembling a small combining experiment to provide experience and data for the ILSE combining experiments. Beam dynamics issues which must be resolved before the ILSE ring can be built include centroid control, longitudinal control, emittance preservation through bends, and insertion/extraction of the beam into/out of the rings. These will be addressed at reduced scale in a sequence of experiments leading to a small "model" recirculator at Livermore. The waveform generators must supply variable accelerating pulses at high repetition frequencies, and accurate time-varying dipole fields with good energy recovery. These requirements are challenging, but advances in solid-state power electronics should make it possible to meet them. Livermore has already achieved 200 kHz bursts at 5 kV and 800 A, but with a non-variable format. Fig. 3 is a diagram of the recirculator experiment.

Readers wanting more information on the program should refer to a recent special issue of Il Nuovo Cimento [6].

5. CONCLUSIONS

In conclusion, it is possible to develop heavy ion inertial fusion at a cost that is low compared to that of other fusion programs. The Heavy Ion Program is greatly leveraged by the Defense Inertial Fusion Program and the worldwide accelerator programs. The long-term cost of electricity compares favorably with that of tokamaks and other energy sources. The first major phase of the accelerator development is the ILSE Program. We have made substantial progress toward ILSE and are in a position to begin construction of the ILSE accelerator when approval is granted.

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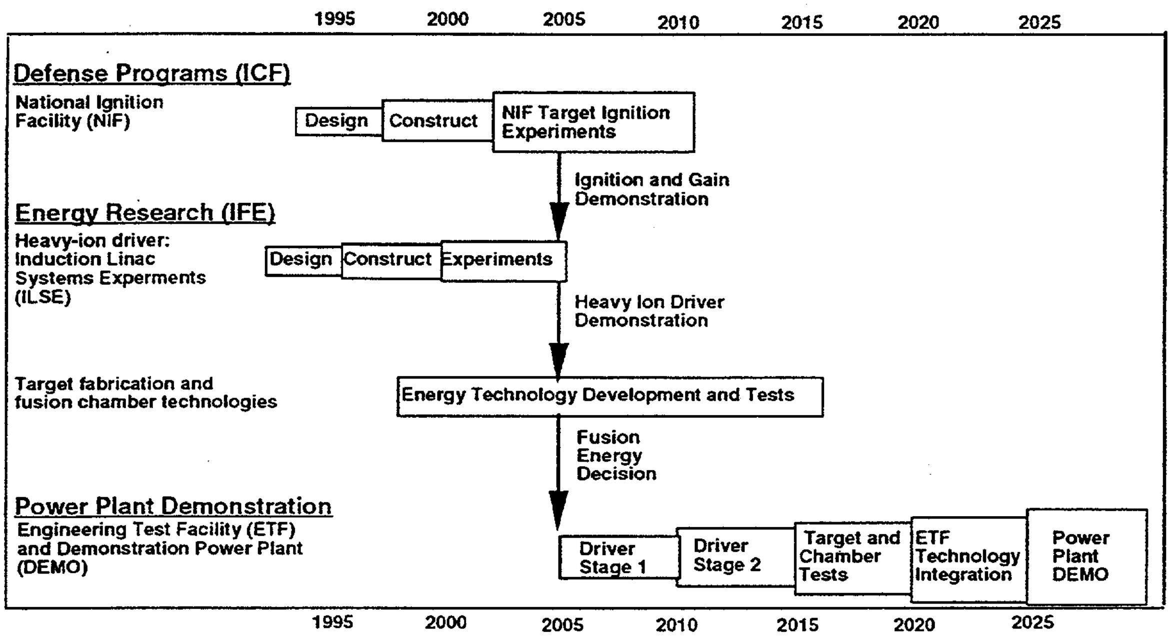
FIGURES

Fig. 1. The Inertial fusion energy development plan.

Fig. 2. Block diagram shows the major systems of ILSE and a possible orientation of it (to approximate scale) in the External Particle Beam (EPB) Hall of the recently shut-down Bevatron.

Fig. 3. Schematic of the small recirculator being developed at LLNL.


1995
2000
2005
2010
2015
2020
2025
Defense Programs (ICF)
National Ignition Facility (NIF)
Design
Construct
NIF Target Ignition Experiments
Ignition and Gain Demonstration
Energy Research (IFE)
Heavy-ion driver: Induction Linac Systems Experments (ILSE)
Design
Construct
Experiments
Heavy Ion Driver Demonstration
Target fabrication and fusion chamber technologies
Energy Technology Development and Tests
Fusion Energy Decision
Power Plant Demonstration
Engineering Test Facility (ETF) and Demonstration Power Plant (DEMO)
Driver Stage 1
Driver Stage 2
Target and Chamber Tests
ETF Technology Integration
Power Plant DEMO
1995
2000
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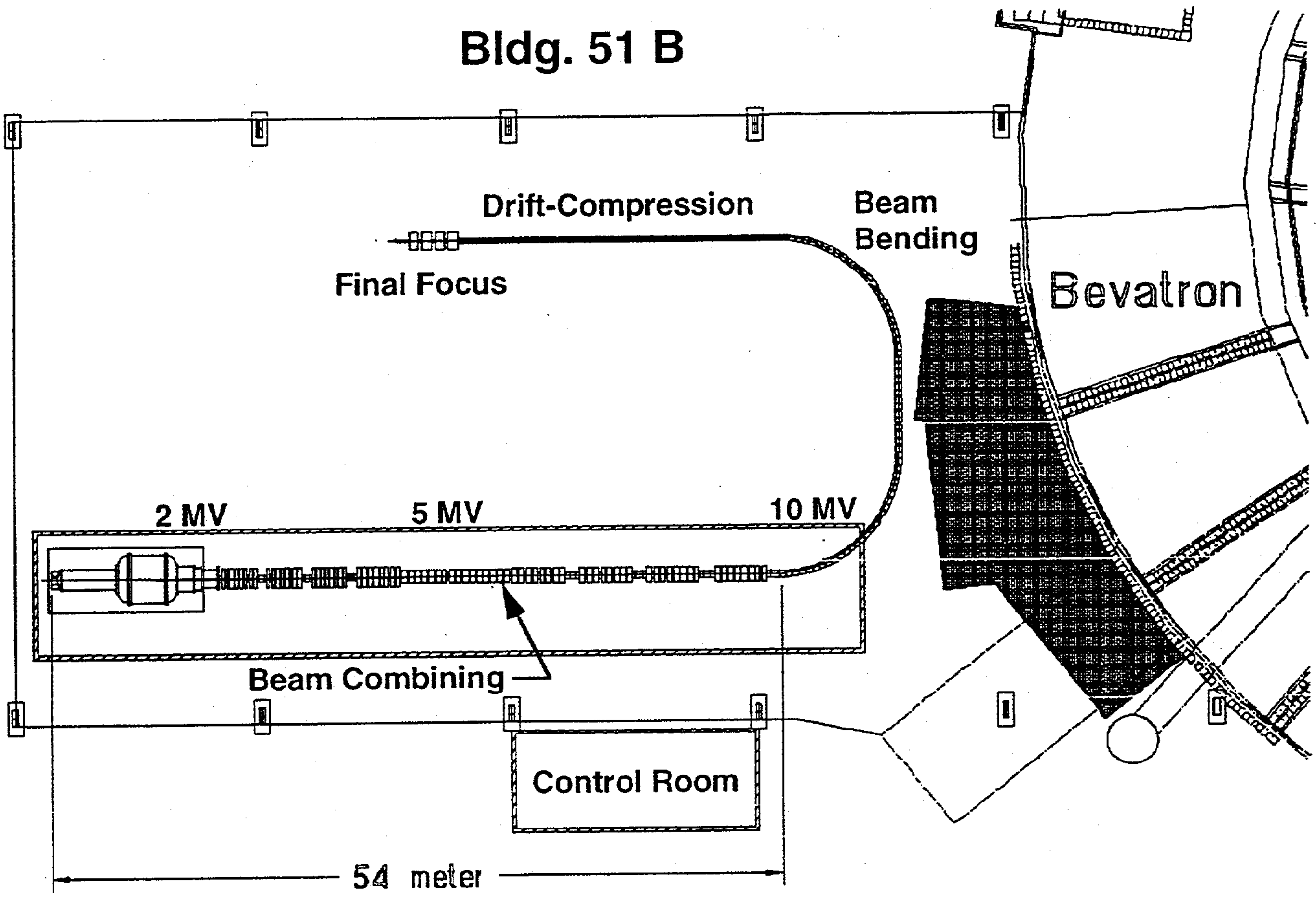
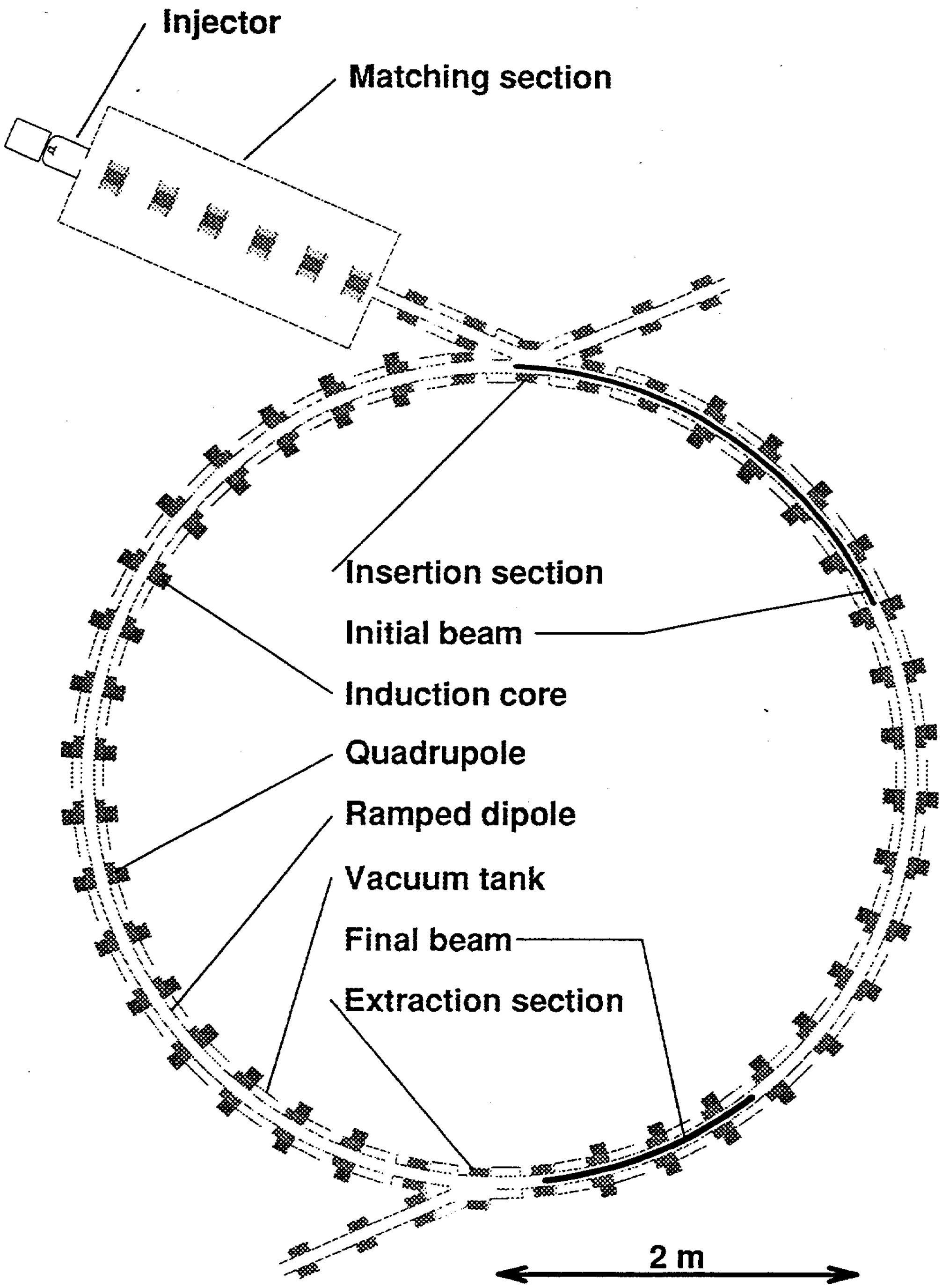
2020
2025

Figure 1



Bldg. 51 B
Drift-Compression
Beam
Bending
Final Focus
Bevatron
2 MV
5 MV
10 MV
Beam Combining
Control Room
54 meter

Figure 2



Ion species: Potassium (mass 39)
Beam energy: 80-320 kV
Beam current: 2-8 mA

Pulse duration: 4-1 μs
Nominal number of laps: 15
Circumference: 14.4 m

Figure 3