LA-UR-82-1192

CONF-820338--8

TITLE: THE U. S. PROGRAM IN HEAVY-ION FUSION

AUTHOR(S): Roger O. Bangerter

LA-UR--82-1192

DE82 015769

SUBMITTED TO: The Symposium on Accelerator Aspects of Heavy-Ion Fusion, Darmstadt, West Germany (April 1982)

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MASTER

THE U. S. PROGRAM IN HEAVY-ION FUSION*

Roger O. Bangerter
University of California
Los Alamos National Laboratory
Los Alamos, New Mexico

I. Introduction

In the United States, inertial confinement fusion (ICF) has been studied for potential application to both commercial energy production and defense. However, funding has come almost entirely through the Department of Energy's Defense Programs. This has created a problem for heavy-ion fusion. Technical reviews of heavy-ion fusion in the U.S. have been favorable.[1] However, the characterisics that make heavy-ion accelerators so well suited for energy production (namely reliability, long lifetime, high-average power capability, and high efficiency) have not been considered essential for defense applications. Furthermore, heavy ion accelerators are a late entry in the ICF competition. For these reasons, among others, defense funding for inertial fusion has been largely concentrated on lasers and single-stage pulsed power accelerators.

We have therefore proposed that heavy-ion fusion accelerator development be transferred to the Office of Energy Research of the Department of Energy. This transfer has not yet occurred, but the outlook is favorable. If the transfer occurs, it will be very encouraging. Transfer will constitute official Department of Energy recognition that heavy ion fusion is truly an energy program.

Unfortunately, the transfer is occurring at a time when the total ICF budget is decreasing. Existing DOE funding has only been sufficient for a single major program at Lawrence Berkeley Laboratory. However, because of the promise and importance of the program Los Alamos National Laboratory is supporting an effort on accelerator technology and target design with discretionary funds. Lawrence Livermore National Laboratory is also continuing to do important work in target design and beam transport.

* This work was performed under the auspices of the U.S. Department of Energy.

II. National Plan for Heavy Ion Fusion

In preparation for the transfer of heavy-ion fusion from Defense Programs to the Office of Energy Research, we were asked to prepare a national plan covering a period of about six years.[2]

If one carefully examines heavy-ion fusion, it becomes apparent that the promise of success is based on six assumptions:

1. It is possible to build an efficient accelerator, at reasonable cost, that can generate high-energy (> 1 MJ) ion beams occupying a small 6-dimensional phase-space volume.

2. The beams from such an accelerator can be focused over a distance of several meters onto a small target located in a reaction chamber. (Small 6 dimensional phase space volume is a necessary, but not sufficient condition, for this to occur.)

3. Our present calculations correctly describe ion energy deposition.

4. The hydrodynamic and thermonuclear behavior of the target is reasonably well described by our numerical simulations.

5. Targets corresponding to our numerical models can be mass produced at acceptable cost.

6. A reaction chamber can be built that economically converts the target products into useful energy and produces target fuels not adequately occuring in nature.

Not everyone agrees that all six statements are assumptions. Some are convinced that accelerator technology and theory have already been adequately tested. Others are convinced that our present calculations of ion energy deposition are adequate and so on. However, we find that there are responsible scientists in heavy-ion fusion, in the larger ICF program, and in the general scientific community who are concerned about the validity of each of the six assumptions.

If we accept the above point of view, we must design a program plan that determines the validity of each of the assumptions in a way that is convincing to us and our scientific colleagues. If we accomplish this, we will be in a position to make sound decisions about the promise and future of heavy-ion fusion.

In order to establish a balanced program covering all 6 areas of research, we have proposed that:

The Office of Energy Research assume responsibility for:

1. Accelerators
2. Beam transport and focusing
3. Beam target interaction (ion energy deposition)

Defense Programs should retain responsibility for:

4. Target theory and experiments relating to implosion and thermonuclear burn

5. Target fabrication

6. Reaction chamber and power plant studies.

Logically, the last area belongs under the Office of Energy Research, but it is currently being supported by Defense Programs as part of the Laser Fusion Program.

To distinguish the new program from the Heavy-Ion Fusion Program, under Defense Programs we proposed to call the new program the Accelerator Inertial Fusion Program (AIF). In this paper, we use both designations. Los Alamos National Laboratory will remain the lead laboratory and provide coordination between Energy Research and Defense Programs.

B. The Accelerator Program

From our first assumption, we note that the accelerator program must address several issues:

- General scientific questions relating to the efficient production and control of high-energy beams with high 6-D phase-space density

- Costs

In addition, there are several different types of accelerators; therefore, the program must also address:

- The choice of accelerator technology.

In addressing these issues, we must obey reasonable fiscal constraints. Even if we assume that all of the scientific problems are solved, it is not realistic in the present U. S. environment, to proceed directly to a large, expensive accelerator ($\geq$ 1 MJ). An intermediate experimental accelerator is required. This accelerator must be large enough to address the accelerator issues and also the focusing and target interaction issues.

We refer to this integrated test of accelerator physics and technology, beam focusing, and energy deposition as the high-temperature experiment (HTE). This name is not meant to imply that energy deposition in high temperature plasmas is the critical issue. Based on all evidence to date, this is unlikely.[3] Completion of the HTE will mark a point at which our first three assumptions will have been tested.

C. Transport, Focusing, and the Beam-Target Interaction

Scaled focusing experiments using electron beams (Rutherford-Maryland collaboration) are currently in progress. Also the channel transport experiments using light ions and electrons may be relevant to heavier ions. However, the HTE will provide the opportunity for focusing experiments on low emittance ion beams, including the possiblity of neutralization.

The ion-target interaction is being studied with light ion at Sandia and NRL and with heavy ions in cold matter at the Unilac and Bevalac. It may also be possible to perform experiments with low intensity beams in preformed plasmas. However, some anomalous effects could depend on beam intensity, it would be most satisfying to test energy deposition in beam-heated plasmas.

Simple considerations suggest that it may be possible to perform very significant physics tests using an accelerator that is much smaller than that required for fusion experiments. Consider a simple experiment such as shown in Fig. 1. Material to be heated by the beam is placed in a hole in a high-Z slab. The high-Z slab partially confines the material reducing hydrodynamic expansion. It also reduces radiative losses in all directions except into the beam. If we ignore hydrodynamic motion (or crudely include it as a correction to the specific heat capacity c), we can write an approximate equality involving the irradiance I, ion range R, specific heat capacity c, temperature T, Stefan Boltzman constant , and time t.

$$I = R\,\frac{d(cT)}{dt} + \sigma T^4$$

If we make the approximation that c is constant, we can integrate this equation obtaining.

$$x = \frac{c}{4\sigma}\left[2\tan^{-1}y - m\left(\frac{1-y}{1+y}\right)\right]$$

where $x = t\,T^3_{max}/R$, $y = T/T_{max}$, and $\sigma T^4_{max} = I$.

A plot of x vs y is shown in Fig. 2. As expected for constant irradiance and heat capacity, the temperature increases approximately linearly with time until radiative losses become important. The temperature then asymtotically approaches T_{max}. We define a time τ, corresponding to the intersection of a line tangent to the curve at $x = 0$ and the line $y = 1$. At $t = \tau$ the temperature has reached about 0.86 T_{max}. The maximum temperature predicted by this simple model is in good agreement with the results of numerical simulations shown in Fig. 3.

Some arguments[2] indicate that it may be easier to obtain high irradiance with an HTE accelerator using ions such as sodium or potassium rather than very heavy ions; however, it is still expected that heavy ions are the correct choice for a large fusion driver.

These lighter ions should provide an adequate test of accelerator physics and technology. In order to reduce costs, it is interesting to examine accelerators with kinetic energy in the neighborhood of 100 MeV. However, it is not *a priori* evident that such an accelerator could provide adequate tests of focusing and deposition. In order to investigate this, we have calculated a large number of quantities that might be of interest in any theory of focusing or energy deposition. We have done this for four different examples of accelerators, a fusion driver, PBFA, and two examples of HTE accelerators. The results are given in Table I. We have also included the possibility of doing experiments with existing accelerators in a plasma preheated to about 50 eV. The HTE examples have not been designed and the parameters given may not be particularly reasonable from an accelerator point of view. For PBFA, we assumed 4 MeV protons with an irradiance of 10^{13} w/cm^2, well below the expected value. The quantities given in Table I are broken down into four categories. The first category specifies some of the accelerator characteristics. The second category gives the characteristics of a target plasma. The time τ as defined in Fig. 2 was multiplied by power to compute E under accelerator characteristics. The important point is that the temperature and time scales associated with PBFA and the HTE examples are within a factor of a few of those ultimately required. Some plasma parameters of interest such as the electron plasma frequency are independent of temperature. Others, such as the Debye length and electron thermal velocity vary only as the square root of temperature. Still others such as resistivity vary more rapidly with temperature, and some depend on both temperature and density. The density can be varied by large factors. Thus by many measures, PBFA or the HTE examples enable us to approach the parameter range of ultimate interest very closely. In all cases, the temperature is high enough to test range shortening.[4]

The third category gives the characteristics of the beam. These are given in an unconventional form in an effort to motivate simply the combinations chosen. For example, one might expect any plasma to respond to current density. The beam particles in turn respond to electric and magnetic fields. This response might be expected to depend on Z/p or Z/T where p and T are momentum and kinetic energy, respectively; thus, the quantities JZ/p and JZ/T have been tabulated. Fully stripped ions are assumed. It is recognized that these can be expressed in terms of more conventional plasma theory parameters. For example JZ/p is proportional to the square of the beam plasma frequency, which appears to a positive power in the growth rates for many beam-plasma instabilities. It should be noted that growth rates usually decrease with increasing beam temperature (energy or angular spread). The PBFA beams are likely to be quite hot, and this must be taken into account in extending PBFA results to other cases.

The fourth category gives quantities that might be of interest for focusing. The parameter λ is charge per unit length. The quantities in this category assume singly charged ions. Since scaling also depends on beam angular divergence and focal radius, a large parameter region can be explored with an FTE.

We emphasize that Table I is neither complete nor rigorous. Some of the quantities listed may be unimportant or important quantities may have been omitted. The purpose of the table is to suggest that by a large number of measures, PBFA together with an HTE and existing accelerators will be able to explore the focusing and deposition issues in an interesting parameter regime. There is a great deal of flexibility in choosing HTE parameters. The only requirement specified in our National Plan is that the HTE produce a temperature $\geq$50 eV. If this temperature is achieved, the preliminary considerations listed above suggest that the HTE together with other possible experiments will provide adequate tests of our assumptions about accelerators, focusing, and deposition.

We currently hope to have the HTE on-line in about 1989. A two stage program has been proposed to achieve this goal. The first stage consists of accelerator research and development. The second stage consists of actual assembly of the HTE. This program with proposed funding is outlined in Fig. 4.

IV. Speculations on Program Direction after the HTE

This section contains the author's speculations. These speculations are not part of any official plan or policy.

In the 1990's fusion research may be entering the engineering phase. For most fusion concepts, this will be expensive. In particular for systems burning DT, tritium self-sufficiency seems essential since only very small quantities of tritium occur naturally. Tritium breeding ratios of about 2 appear possible so that a large fraction of the solid angle of the reactor must be surrounded by tritium breeding materials. For low power density devices that only work in large sizes, even the first test reactors may be very expensive.

It would be very useful if one could begin reactor engineering tests and tritium breeding at a small scale. Heavy-ion fusion may offer this possibility. Consider the following parameters:

Energy	0.1 - 1 MJ
Repetition Rate	~10 Hz
Target Gain	~1

Such a machine would produce 1-10 MW of fusion power (4×10^{17} - 4×10^{18} neutrons/s). The accelerator is small compared to a power plant driver. The target gain is also low. By the time such an accelerator could be built, we might have considerable confidence in low-gain targets, but we may not yet have demonstrated high gain.

The reaction cavity required to contain such small yields might be relatively small and inexpensive and still allow tritium self-sufficiency and engineering development. The time scale for such a facility depends on the larger ICF program and on the HTE. If the HTE accelerator has very high performance or if it is a module or part of a larger accelerator, the time to a small reactor test facility might be shortened.

It is certainly to early to claim that heavy-ion fusion has a particular advantage over other fusion schemes. Nevertheless, the promise of such advantages is sufficiently real to justify a healthy program and demand the serious attention of the scientific community.

TABLE I

		R	PBFA	HTE 1	HTE 2	BEVALAC/ UNILAC/ OTHER
BEAM	Z	92	1	11	92	All[b]
	A	238	1	23	238	All
	T (MeV)	10^4	4	100	10^4	All
	P (W)	10^{14}	10^{13}	10^{11}	10^{12}	NA[c]
	E (kJ)	630	300	2.8	50	NA
	r (cm)	0.25	0.56	0.1	0.1	NA
PLASMA	T_{max} (eV)	265	100	75	134	~50[d]
	τ (ns)	6.3	30	28		
DEPOSITION	[illegible]	0.3	0.1	0.1	0.3	All
	R (g/cm^{-2})	0.1	0.01	0.01	0.1	All
	N (cm^{-3})	3.5×10^{13}	5.2×10^{15}	6.6×10^{13}	2.2×10^{12}	NA
	ΔN (cm^{-3})	3.3×10^{15}	5.2×10^{15}	7.3×10^{14}	2.0×10^{14}	NA
	[illegible] (amp·cm^{-2}·MeV^{-1})	4.3×10^4	[illegible]	3.5×10^4	2.7×10^3	NA
	[illegible] (amp·cm^{-2}·MeV^{-1})	6.4×10^2	[illegible]	1.9×10^3	4.0×10^2	NA
TRANSPORT	[illegible] (coul·cm^{-2}·MeV^{-1})	1.1×10^{-10}	[illegible]	3.3×10^{-9}	1.1×10^{12}	NA
	[illegible] (amp·MeV^{-1})	[illegible]	[illegible]	[illegible]	1.5×10^{-3}	NA

a Beam temperature may be high

b All means almost all of interest

c Not Applicable

d Plasma [illegible] produced by external heating

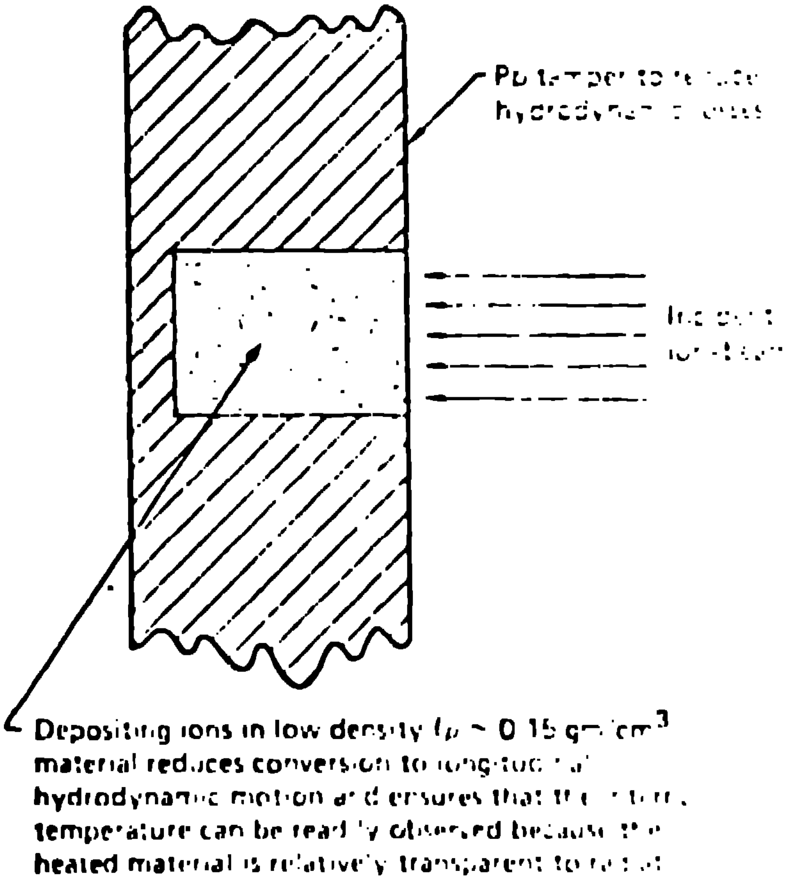


Fig. 1 Target geometry visualized for the High Temperature Experiment. A low Z cylindrical target disk would be encased in a high Z tamper to postpone the hydrodynamic disassembly of the target.

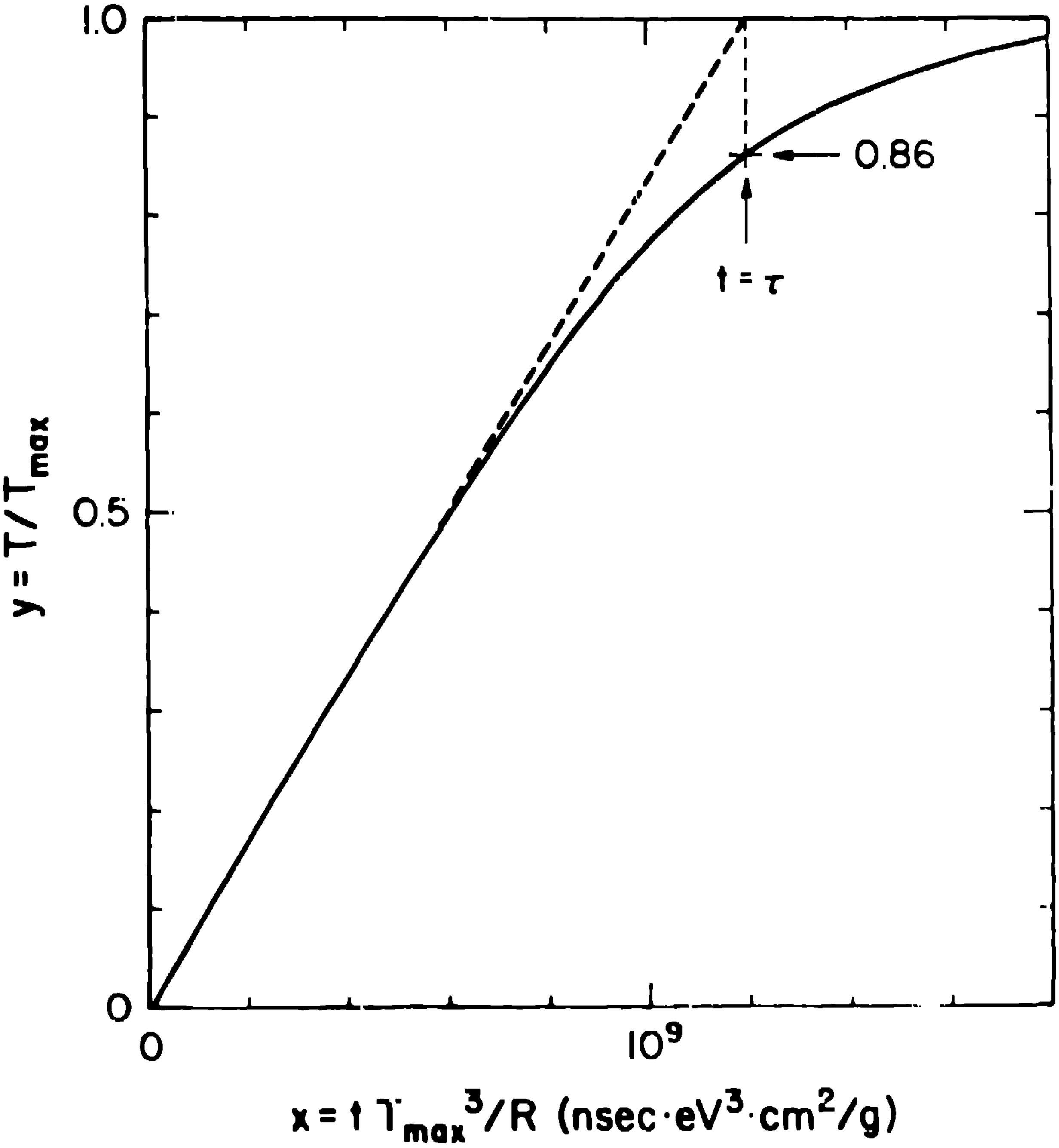
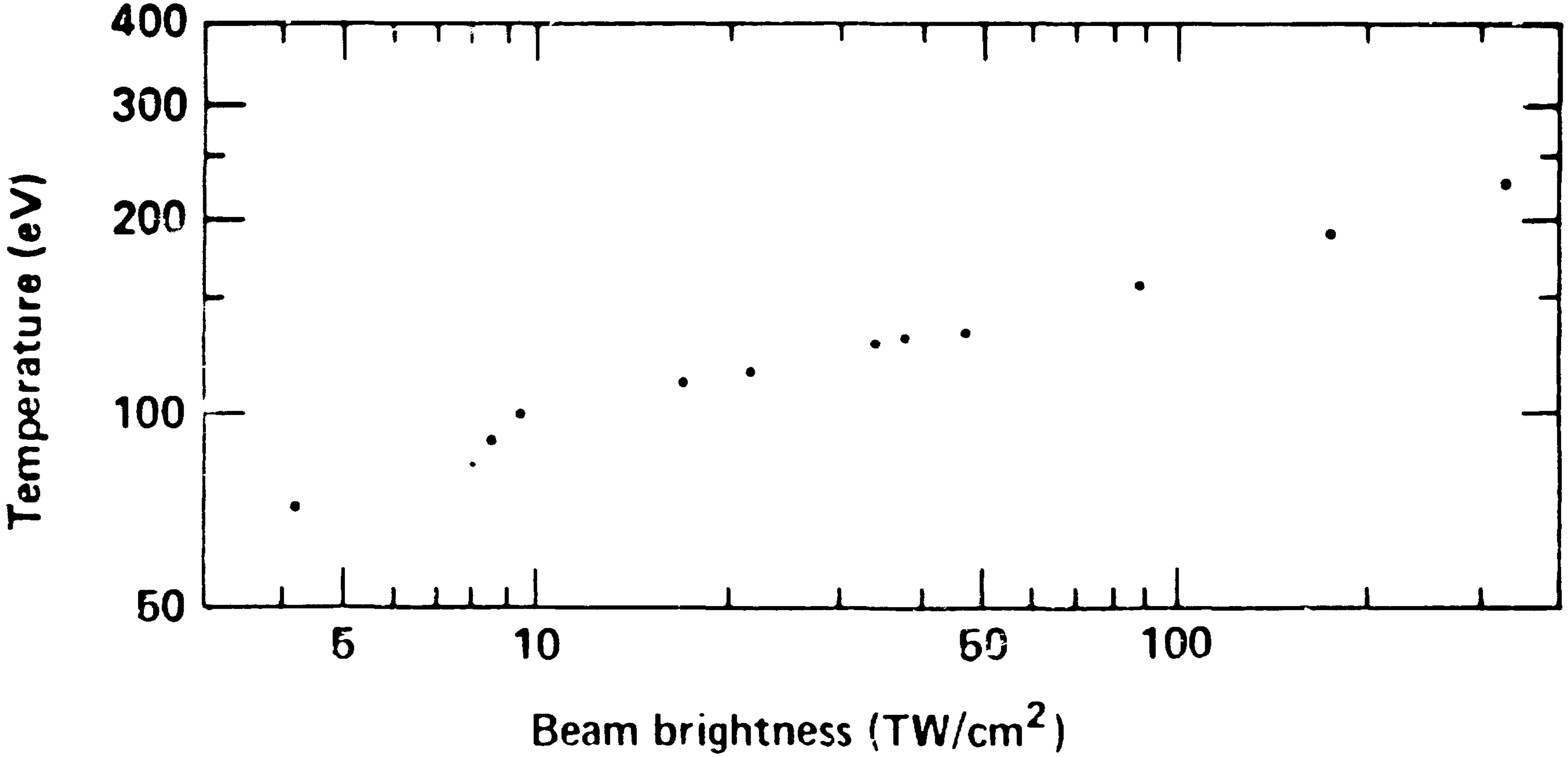


Fig. 2 Scaled temperature as a function of scaled time for the experiment illustrated in Fig. 1. This curve is based on the crude model discussed in the text. The time $t = \tau$ is defined, as shown.


400
300
200
100
50
Temperature (eV)
5
10
50
100
Beam brightness (TW/cm²)

[illegible]

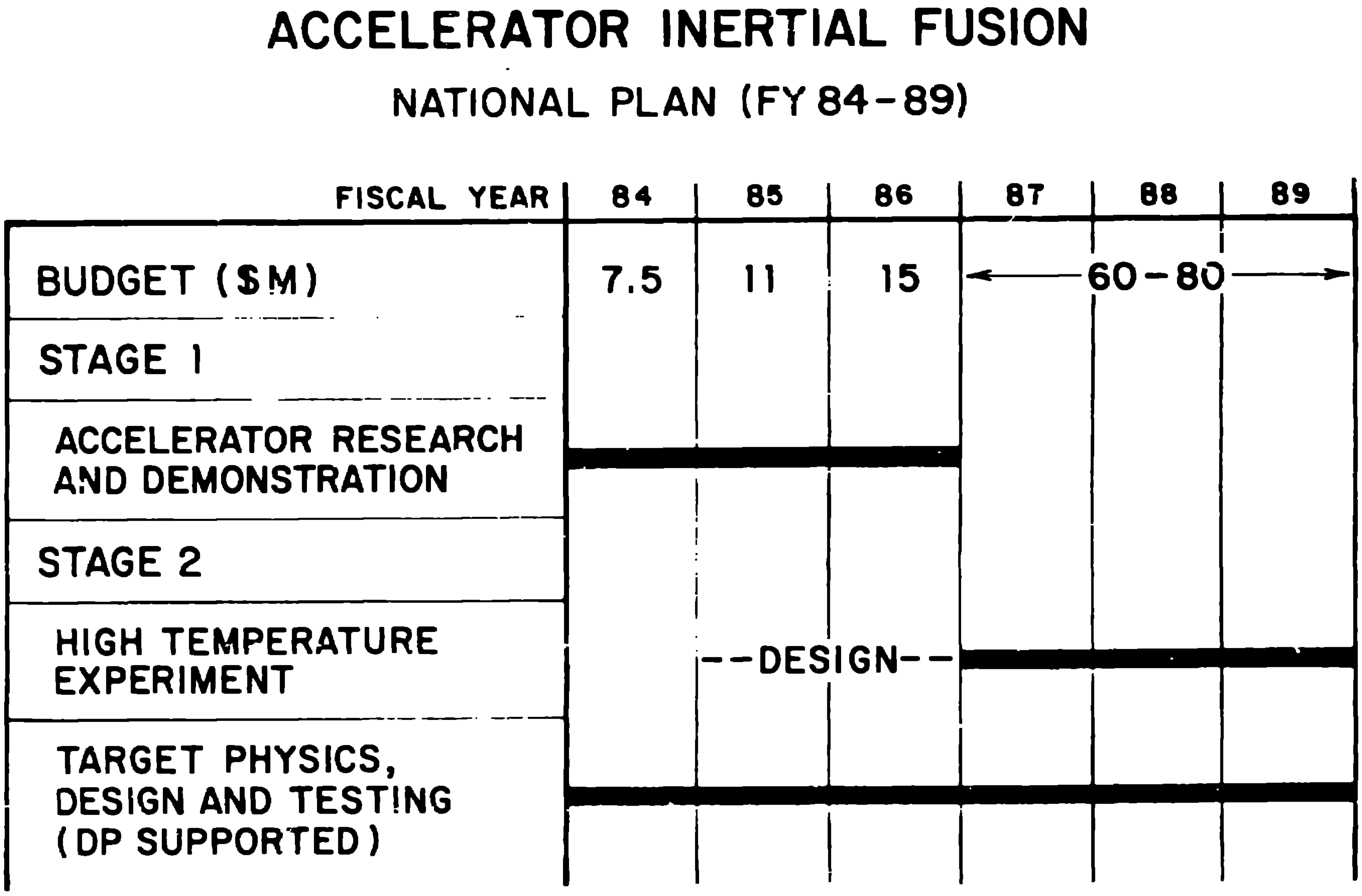


Fig. [illegible] The program schedule and budget for the Accelerator Inertial Fusion National Plan.

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