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HEAVY ION FUSION SYSTEMS ASSESSMENT STUDY*

Donald J. Dudziak
Los Alamos National Laboratory
University of California
Los Alamos, New Mexico 87545

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and

W. B. Herrmannsfeldt
Stanford Linear Accelerator Center
Stanford University, Stanford, CA 94305

Abstract

The Heavy Ion Fusion Systems Assessment (HIFSA) study was conducted with the specific objective of evaluating the prospects of using induction linac drivers to generate economical electrical power from inertial confinement fusion. The study used algorithmic models of representative components of a fusion system to identify favored areas in the multidimensional parameter space. The resulting cost-of-electricity (COE) projections are comparable to those from other (magnetic) fusion scenarios, at a plant size of 1000 MWe. These results hold over a large area of parameter space, but depend especially on making large savings in the cost of the accelerator by using ions with a charge-to-mass ratio about three times higher than has been usually assumed. The feasibility of actually realizing such savings has been shown: (1) by experiments showing better-than-previously-assumed transport stability for space charge dominated beams, and (2) by theoretical predictions that the final transport and compression of the pulse to the target pellet, in the expected environment of a reactor chamber, may be sufficiently resistant to instabilities, in particular to streaming instabilities, to enable neutralized beams to successfully propagate to the target. Neutralization is assumed to be required for the higher current pulses that result from the use of the higher charge-to-mass ratio beams.

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So

Objectives

The Heavy Ion Fusion Systems Assessment (HIFSA) study was organized to deal with a specific premise, and had as its charge, a specific set of objectives. The premise, most directly stated, is that fusion in general, and the Heavy Ion Fusion (HIF) approach to Inertial Confinement Fusion (ICF) in particular, appears to be so costly and requires scaling to such large power plants that it has not been possible to design a program that would be attractive to the electric utility industry.

The most concise statement of the objectives of the study, which is intended to find a solution to this programmatic dilemma, was drafted by the three DOE offices that are funding the HIFSA study:

> "Briefly stated, the objective of the study is to perform an assessment of heavy ion inertial fusion systems based on induction accelerators, including representative reactor systems, beam focusing and final transport, target design, and system integration. Emphasis will be given to systems for electric power production and to design innovations and parameter ranges which offer credible promise of reducing system size and cost. No attempt will be made to review heavy ion fusion as a whole, nor current programs, except by inference and in summaries of previous studies. Rather, effort will be concentrated on system and subsystem conceptual design and analysis, including cost/performance models for studying and exhibiting major system parameter variations. Identification of needed R&D will be included. It is expected that the study will be used to guide the direction of future heavy ion fusion programs in the U.S., as well as fill a major gap in current fusion program studies."

Note especially the last requirement, "(to) fill a major gap in current fusion program studies." At each of the two previous symposia in this series results were presented, by the laboratories of the host nation, from comprehensive design studies, HIBALL[1] and HIBLIC[2], respectively. In sharp contrast to the rf accelerator technology featured in both of these studies, the US program[3] has for several years concentrated on the single-pass induction linac approach. It seems incumbent upon us to present a study that will fairly examine the systems aspect of the induction linac as a driver for HIF.

Background

In recent years, various critics[4] have expressed their opinion that, "...even if fusion is found to be technically feasible, at the costs and with the complexities indicated by current estimates, no one needs it." The standard arguments in favor of HIF have always included the economic advantages of high efficiency drivers, the technical simplifications resulting from the separation of driver and reactor, the advantages of the extensive experience with charged particle accelerators, etc. However, the cost of the accelerator system, added to the cost of the reactor, balance of plant (BOP), etc., means a total cost that requires a large power production capacity in order to achieve adequate economy of scale. For example, the HIBALL plant was designed to include four reactor chambers and had a total capacity of nearly 4000 MWe. Even at this size, the cost per kWh of produced electricity was about the same as projected by studies for magnetic fusion(5).

It is likely that the large system studied for HIBALL was, in fact, a result of assumptions in the point design and not just a derived conclusion of the study. In a conceptual study for a point design, the initial design criteria can predetermine the results. An objective of the present study is to find parameters for smaller sized power plants by examining a broad range of parameters to determine the cost implications of new technical innovations that might permit extending the valid parameter space. The logic here is that, unless one can demonstrate the possible advantage of such an extension, it is hard to get anyone interested in studying the problems that it causes.

A second example of the effects of choosing the initial design criteria can be found in a somewhat earlier study by Westinghouse Electric Corporation(6). Here the potential advantage of a high repetition rate was shown by the results which tended toward lower power costs at the 10 pps limit that the project used for the upper bound for pulse repetition rate for the particular technology that was selected. Because it was clear that power costs more for a lower repetition rate system, one would like to see the result for a higher repetition rate. However, both the accelerator system (an rf accelerator with storage ring current multiplication) and the reactor system (a 10- to 20-m-radius dry wall chamber) were designed for the 10 pps limit.

In contrast to the various point designs, there was one very important systems assessment lead by K. A. Brueckner for the Electric Power Research Institute (EPRI)(7). In this report, Brueckner et al. examined the anticipated cost of electricity for a range of parameters for different drivers. The conclusions, based on the limited technical information available in 1979, was that ion beam drivers are promising candidates for commercial fusion power plants. A much more detailed assessment should be possible now using the new data available from target, reactor, and accelerator studies.

In light of the present economic situation of the utility industry, with nuclear plants being cancelled and virtually all previous projections for future power needs being grossly too high, there is understandably no enthusiasm for large-scale fusion scenarios. Even though any long-range energy forecast will conclude that eventually the world must stop burning vast amounts of fossil fuel and turn to an inexhaustible energy resource, the place of fusion as the preferred power source of the future is certainly not enhanced by these expensive scenarios.

Thus it is incumbent upon proponents of HIF to document the purported advantages of their technology. To make a significant impact, it is necessary to depart from conventional approaches. To reduce the capital cost of a projected plant, which is the largest single stumbling block, the total power rating has to be smaller, and the cost of the accelerator must be reduced.

Parameter Space

There is a very large parameter space available to a systems designer. The usual way of considering a commercial ICF system is to divide it into three parts: the driver, the targets, and the reactor, plus BOP. There are at least two major sub parts, which are, in effect, the interfaces with the first three parts: the beam transport system and the target factory.

The BOP, of course, provides the interface between the reactor and the utility customer. The principal plant performance parameter of interest from the BOP is the thermal-to-electricity conversion efficiency. An important secondary role of the heat exchangers in the BOP is to provide a barrier to prevent diffusion of tritium into the environment. With the exception of the magnetically protected dry-wall concept, no attempt has been made in this study to employ direct, or MHD-type, conversion techniques. The thermal conversion efficiency is principally affected by the temperature of the neutron absorbing material in the reactor wall and by the type of heat exchangers needed.

There have been several ICF reactor concepts studied and reported in varying detail over the last several years. The approach in this study was to choose representative reactors from those available; in particular, those with which the participants in the study were most familiar (usually, the concept they had invented). The risk of significantly biasing the study in this way was offset by the presence of reactor designers from two centers, LLNL and LANL. As anyone familiar with these laboratories knows, they are known for "keeping each other honest." The reactors that were included in the study were a "CASCADE" type in which a spinning drum holds lithium-based ceramic granules against the outer wall by centrifugal force, a "wetted wall" type in which a thin jet of liquid lithium is kept against the wall of a spherical chamber by the centrifugal force of the jet, a magnetic-field-protected dry wall chamber, which was introduced primarily as a generic high repetition rate example (it being recognized that the magnetic field scheme might interfere with beam transport), and the HYLIFE liquid lithium waterfall reactor. The HYLIFE reactor was introduced as an example of a low repetition rate concept that would require a minimum of 0.5 seconds for clearing the chamber between shots. The dry-wall concept could operate up to about 20 pps while the other two concepts could conceivably operate in the range of 5-10 pulses per second.

The issue of reactor repetition rate is important because of its significance as a systems parameter that directly determines many other parameters. For example, a 1000 MWe power plant might reasonably need ~4000 MW of fusion power, equivalent to 2000 J/shot at 2 pps or 800 J/shot at 5 pps. Obviously, these would be very different plants in almost all respects. Repetition rate can be used to illustrate some of the complexities of a systems study. Among the advantages usually cited for heavy ion induction linacs is the intrinsic ability to operate at any reasonable pulse repetition rate. The repetition rate for any reasonable system is thought to be limited by reactor and target injection requirements, usually by reactor clearing time[8].

A simple (and incorrect) illustration is as follows: suppose one builds a 1 MWe HIF power plant designed for 5 pps. If after tests it turns out that all components will operate as well at 6 pps, then it would appear that the plant could produce 20% more power for the same capital cost, and the cost of electricity will be (almost) 20% less. Superficially this may appear to be correct, but it is wrong because, from a systems standpoint, it is no longer the 1 MWe plant that was designed. Because the specification for BOP equipment was for 1 MWe, if the system is to operate at 6 pps, the per shot yield must be reduced. This implies lower driver energy and lower target gain (because the gain curve is assumed to be a monotonically rising function of driver energy). The result is that the product ηG is reduced (where η is driver efficiency and G is overall fusion gain). However, the lower energy driver costs less assuming, as we have, that the driver is a heavy ion accelerator easily capable of the higher repetition rate. Without knowing the specific dependance of both the ηG function and the driver cost, it is not possible to say whether the increased repetition rate will increase or decrease the COE. It is possible to say that there can be an optimum repetition rate, above or below which the COE is higher. The happy result from this study, which we will examine in the next section, is that the nearly optimum repetition rates lie in a broad range for COE, and are around 5 to 10 pps, where feasible reactor concepts exist. An interesting sidelight is the issue of cost of the driver for higher repetition rate. Some people have expressed concern about higher cost for a higher repetition rate heavy ion accelerator. As we have seen, the higher repetition rate accelerator will cost less for fixed electric power, because it is, in fact, a less powerful machine.

It was recognized quite some time ago that the key to reduced cost for HIF was to reduce the cost of the accelerator. A program known as LIACEP was written at the Lawrence Berkeley Laboratory (LBL) to find optimum design parameters for the induction linacs being studied. In an earlier paper given at the Palaiseau Conference[9], a number of options for reducing the cost of the linac were examined. Several of these, such as increasing space charge limited current by decreasing the allowed minimum betatron tune, were based on the hope that future experiments would confirm the feasibility of the idea. The lower minimum tune is, in fact, one of the important experimental advances of the HIF program.

Study Results

Two important computational tools were developed for the study:

1. The linac optimization program LIACEP was extensively rewritten, and
2. The program ICCOMO was written to permit examination of large areas of commercial plant parameter space to find local optima.

Probably the most important technical results of the study came from reexamining the cost-saving ideas that were in the Palaiseau paper. The report by Lee[10] at this symposium shows how some of these ideas, modified by newer experimental results, make it possible to envision very significant cost reductions by (especially) using higher charge-to-mass ratios. Most of the study was done for $q = +3$, $A = 130$. In fact, the results would be scarcely affected if $A = 200$ were used.

The methods and results from the systems study are extensively reviewed in other papers at this symposium[11–13]. Readers are referred to these papers for the assumptions and methods that were employed and as reviewers might, we would like to single out some of the most significant (to us) results.

In Fig. 1, we display the results from the study for the "wetted wall" reactor concept. The data plotted are COE vs. repetition rate for five different types of targets. A number of fondly cherished ideas are quickly demolished by this plot:

1. High repetition rate is always better. Not true because the ηG product suffers at high repetition rate, as was discussed earlier. The result is that the cost of providing for recirculating power, and also the cost of targets, begin to dominate the COE. On the other hand, 3 pps is a lot better than 1 pps, which is the design repetition rate for the lithium waterfall reactor concepts.

2. Symmetric targets, which may use the beam energy more efficiently, can result in lower COE. Probably not true because of the cost of the transport system.
3. Higher gain targets are important. Partly true, but not by much (note the depressed scale), and even then only if they don't cost more or need better beam quality. The benefit is small (~5%) because the old standard single shell target still should have an adequate ηG product. Since "Advanced Concept" is a euphemism for "using some untested concepts to improve target performance", it is important to note that such hopes, while potentially useful, are not necessary for competitive COE from HIF.

In Figs. 2 and 3, we display two sets of bar charts showing the "near optimum parameter ranges" for different target concepts and reactor designs. Each bar covers the lowest 5% of COE for that combination. Note that this is for $q = 3$, so the accelerator voltage is reduced by a factor of three compared to an accelerator for $q = 1$. The accelerators are thus much shorter than had been assumed previously, and hence the driver cost is reduced by a factor of about two. The lowest COE results for the granular wall and the wetted wall. Both of these are near optimum in the broad range 3-9 pps and 6-12 GeV.

Finally, in Fig. 4 we display the comparison of cavity types for the single shell target with 16 beams in a two sided illumination scheme. Note that the wetted wall and granular wall types are very close in minimum COE (too close for anyone except their designers to get very excited about). Perhaps here the real message is absolute COE. This study was performed by the McDonnell-Douglas company, under EPRI funding, using methods they had applied previously to magnetic fusion studies. In spite of the requirement for (only) 1000 MWe, the COE is reasonably competitive with other fusion studies, and other technologies. Thus, HIF is in the race.

It was recognized long ago that the HIF drivers can service several reactors. In HIBALL, four reactors were used. Thus, these results from the HIFSA study penalize HIF by limiting the requirement to 1000 MWe. The study looked at the COE for a 500 MWe plant, and found it ~40% higher, for a 2000 MWe plant the COE is reduced by ~25%. One would not expect anything else (the rules of economy of scale cannot be repealed) but it is encouraging to find that even at 500 MWe, the COE is not out of sight.

Conclusions and Recommendations

Among the accomplishments of the HIFSA study are:

1. The development of the codes LIACEP and ICCOMO for future optimization of HIF systems is a significant and tangible product from this study.
2. The discovery that optimal repetition rates exist in a broad minimum for COE, in the range 3-9 pps, can guide future reactor designs.
3. The understanding that potentially major reductions in the cost of induction linacs result from using higher charge-to-mass ratios and multiple beams. The potential savings result directly from the experimental progress made in stable beam transport for intense ion beams in the SBTE and MBE-4 experiments at LBL.

It is worthwhile to note that, although the study was done mostly for $q = 3$, $A = 130$ or $A = 200$, very similar results can be obtained for $q = 1$, $A = 67$. The reasoning is that, while there is good progress with MEVVA sources for multiple-charged heavy ions, it may be that some price must be paid (for example, in higher emittance). With the same electrical current, a beam of $q = 3$, $A = 200$ ions would have the same beam properties as a beam of $q = 1$, $A = 67$ ions, except that the latter would have slightly longer range. The range difference becomes less noticeable at lower kinetic energies, corresponding to the shorter range favored for better target performance. Thus, the accelerator R&D should continue now without necessarily concentrating on how to make a good charge-state-plus-three ion source.

One important conclusion of the study, not discussed here yet is that with the higher currents it is certainly necessary to invoke neutralization during final transport. Work by Stroud[14] gives confidence that streaming instabilities will not destroy the emittance during transport through the target chamber.

One of the principal objectives of this study was to help define future directions for the HIFAR program. We noted that the significant cost savings identified by the study are based on experimental results in the SBTE and MBE-4 experiments at LBL. Both of these are very small scale experiments. It is most important to move into significant beam power and particle velocity, if for no other reason than just to gain more relevant experience. History has taught us to expect new phenomena when key parameters, such as beam power, are extended by orders of magnitude. The LBL group has proposed a machine called ILSE (Induction Linac System Experiment) which has scaled power and higher particle velocity as its chief goals.

Historically, HIF was considered to be the ion beam approach that could use vacuum transport to hit the pellet, and avoid all the messy complexities of plasma physics. The current understanding of reactor chamber physics, and the use of higher currents (higher charge state, lower kinetic energy) makes this old hope wishful thinking. Beams will neutralize and neutralization must be invoked just to hit the target. The neutralization phenomena must be studied and any possible relevant experiments must be planned. Also, the handling of intense beams in bending and focusing systems must be demonstrated. The high intensities needed at the pellet require longitudinal compression of the pulse as it nears the target. The expectation is that longitudinal space charge forces will control the longitudinal momentum spread, and permit adequate control of chromatic aberrations. This needs verification both by simulation and by experiments. Fortunately, it should be possible to perform relevant experiments at low kinetic energies.

The other areas in which R&D is especially needed have all been known for some time. The cost advantages of multiple beams in the accelerator, for example, are well known, and MBE-4 has demonstrated that at least four beams can be accelerated together. Techniques for instrumenting a multiple beam accelerator are needed for orbit diagnostics and corrections.

The largest number of beams is needed in the low velocity part of the linac. After the injector area, merging of beams can make the magnetic transport system much more economical. Experiments with merging are planned for the ILSE program.

Significant cost savings can be made with good engineering, especially of induction cores and pulsers. Except for the areas noted above (merging and final transport) most of the physics issues for HIF are in hand. Now we need practical experience with engineering and operation of high intensity systems.

Any list of HIF R&D contains ion source development. Although a good start has been made, much work remains on the 16-beam, 2-megavolt injector that is being built at Los Alamos.

References

1. "HIBALL-II, An Improved Heavy Ion Beam Driven Fusion Reactor Study," Kernforschungszentrum, Karlsruhe, Report KfK-3480; Fusion Power Associates, FPA-84-4; University of Wisconsin, UWFDM-625, July 1985.
2. "HIBLIC-I, Conceptual Design of a Heavy Ion Fusion Reactor," Research Information Center, Institute for Plasma Physics, Nagoya University, Report IPPJ-663, January 1985.
3. R. O. Bangerter, "Accelerator Inertial Fusion – A National Plan for the Development of Heavy Ion Accelerators for Fusion Power," Los Alamos National Laboratory, LA-UR-81-3730 (1981).
4. For example, L. Lidsky, "The Trouble With Fusion," MIT Technology Review, October 1983.
5. C. C. Baker et al., "STARFIRE – A Commercial Fusion Tokamak Power Plant," Argonne National Laboratory, ANL/FDP/80-1, September 1980.
6. E. W. Sucov et al., "Inertial Confinement Fusion Central Station Electric Power Plant," Westinghouse Electric Corporation, Pittsburgh, PA 15236, WFPS-TME-81-001 (1981).
7. K. A. Brueckner, "Assessment of Drivers and Reactors for Inertial Confinement Fusion," Electric Power Research Institute, Palo Alto, CA 94304, EPRI AP-1371 (1980).
8. R. Peterson, "Repetition Rates in Heavy Ion Driver Fusion Reactors," Presented at the International Symposium on Heavy Ion Fusion, HIF-86, Washington, D.C., May 1986.
9. A. Faltens, E. Hoyer and D. Keefe, "A 3-megajoule Heavy Ion Fusion Driver," Proc. IV International Topical Conference on High Power Electron and Ion Beam Research and Technology, Palaiseau, France (1981).
10. E. Lee, "Induction Accelerator Model for HIF Systems," HIF-86, May 1986.
11. J. Hovingh et al., "The Cost of Induction Linac Drivers for Inertial Fusion for Various Target Yields," HIF-86, May 1986.
12. D. Zuckerman et al., "Performance and Cost Modelling of a Linac Driver HIF Power Plant," HIF-86, May 1986.
13. D. Driemeyer et al., "Influence of Systems Optimization Considerations on LIA Drivers," HIF-86, May 1986.
14. P. Stroud, "Heavy Ion Beam Transport in ICF Reaction Chambers," HIF-86, May 1986.

Figure Captions

1. COE as a function of repetition rate for different target types. The wetted wall chamber is assumed and 16 beams are used in a two sided illumination scheme.
2. The "near optimum ranges" are shown for COE within 5% of the minimum for each combination of parameters. The lowest power costs are for the wetted wall and granular wall. The bars refer to target types: SS for single shell, RM for range multiplied, DS for double shell, SYM for symmetric illumination (which cannot be used in the granular wall concept) and ADV for advanced design.
3. The labels are the same for Figs. 2 and 3. The low repetition rate for liquid wall (HYLIFE) limits it to high beam energy, and raises the COE. The low yield limit for the unprotected dry wall limits it to very high repetition rates, which raises the COE because of the resulting lower ηG product. The other two schemes find the middle of the optimum range.
4. The COE is compared for different cavity types. The conclusion is that optimum repetition rates lie in the range 3-9 pps, and that more work should be done on reactors capable of such rates.

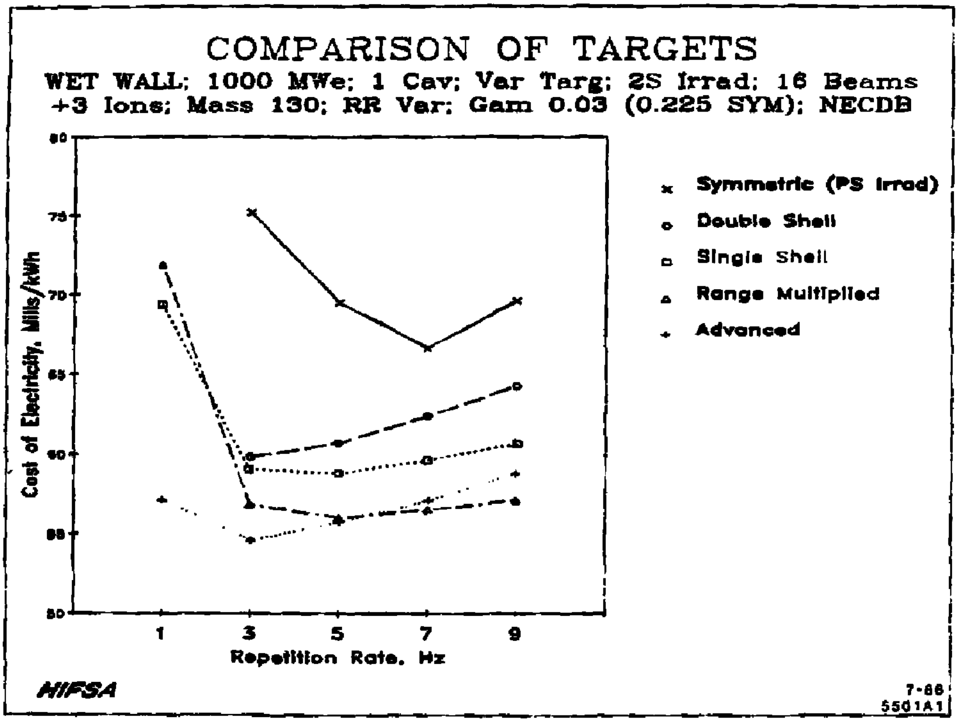

COMPARISON OF TARGETS
WET WALL; 1000 MWe; 1 Cav; Var Targ; 2S Irrad; 16 Beams
+3 Ions; Mass 130; RR Var; Gam 0.03 (0.225 SYM); NECDB
Cost of Electricity, Mills/kWh
80
75
70
65
60
55
50
1
3
5
7
9
Repetition Rate, Hz
Symmetric (PS Irrad)
Double Shell
Single Shell
Range Multiplied
Advanced
HIFSA
7-86
5501A1

Fig. 1

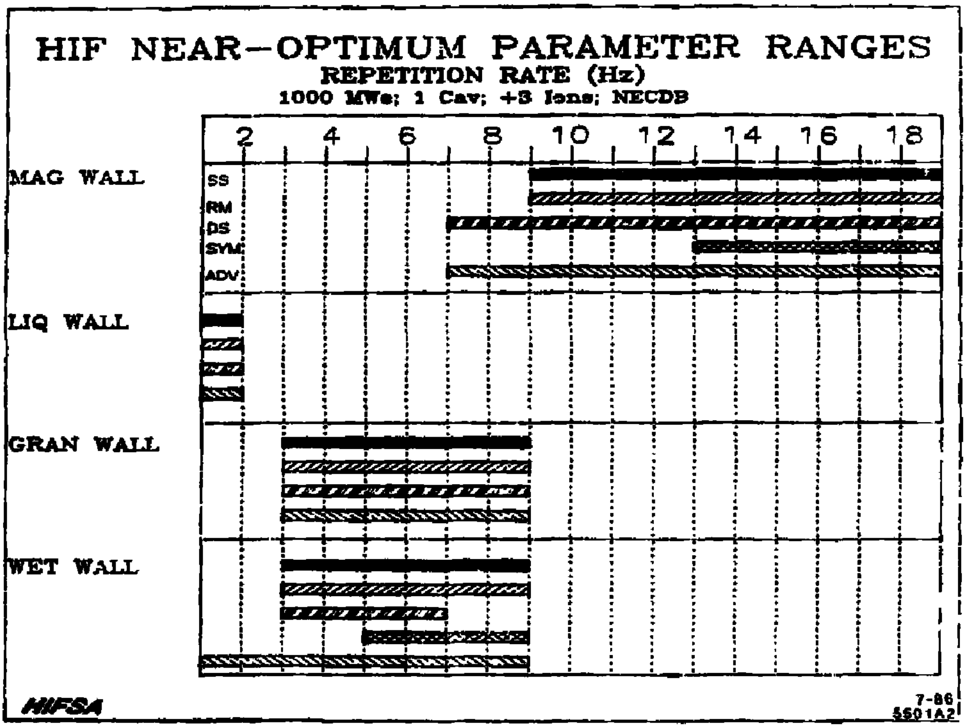

HIF NEAR-OPTIMUM PARAMETER RANGES
REPETITION RATE (Hz)
1000 MWe; 1 Cav; +3 Ions; NECDB
2
4
6
8
10
12
14
16
18
MAG WALL
SS
RM
DS
SYM
ADV
LIQ WALL
GRAN WALL
WET WALL
HIFSA
7-86
5501A2

Fig. 2

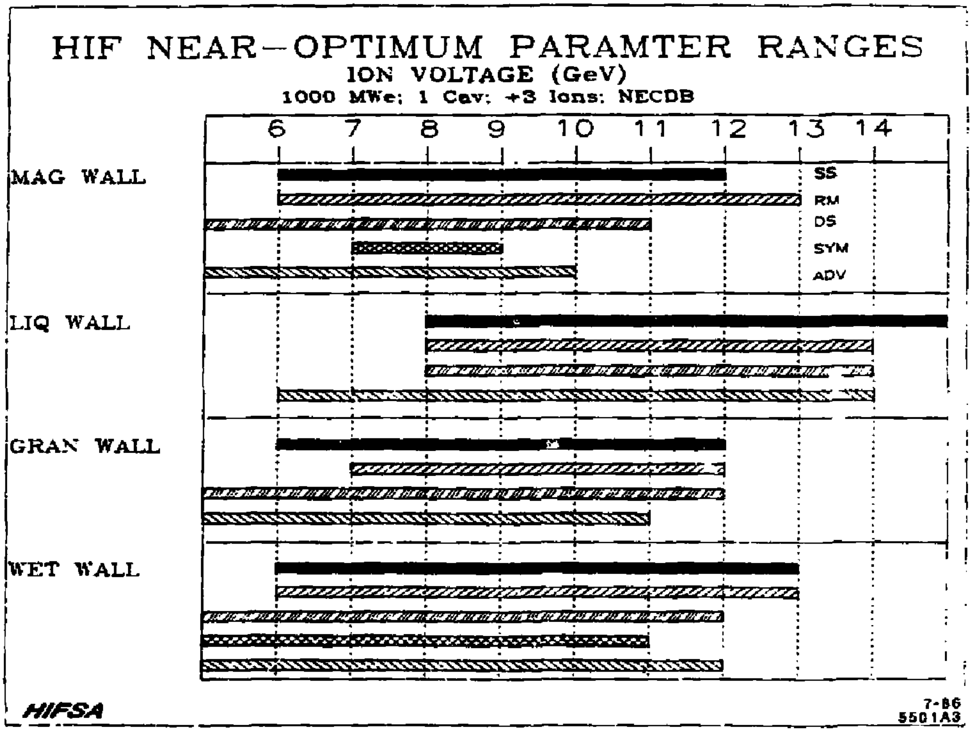
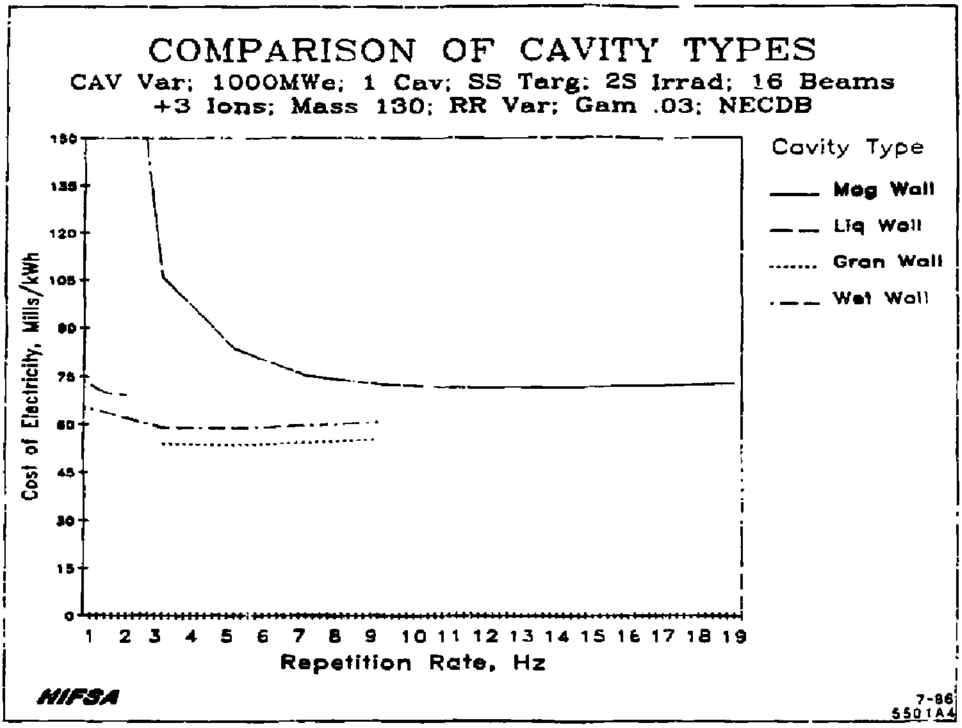

HIF NEAR–OPTIMUM PARAMTER RANGES
ION VOLTAGE (GeV)
1000 MWe; 1 Cav; +3 Ions; NECDB
6 7 8 9 10 11 12 13 14
MAG WALL
SS
RM
DS
SYM
ADV
LIQ WALL
GRAN WALL
WET WALL
HIFSA
7-86
5501A3

Fig. 3



COMPARISON OF CAVITY TYPES
CAV Var; 1000MWe; 1 Cav; SS Targ; 2S Irrad; 16 Beams
+3 Ions; Mass 130; RR Var; Gam .03; NECDB
Cost of Electricity, Mills/kWh
Repetition Rate, Hz
Cavity Type
Mag Wall
Liq Wall
Gran Wall
Wet Wall
NIFSA
7-86
5501A4

Fig. 4