MASTER

Systems Assessment of Heavy Ion Beam Fusion Drivers

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SYSTEMS ASSESSMENT OF HEAVY ION
BEAM FUSION DRIVERS

Final Report

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Systems Assessment of Heavy Ion Beam

. Fusion Drivers

Abstract

A systems analysis for a fusion reactor utilizing a heavy ion beam-pellet fusion is carried out to evaluate the performance of several potential "drivers". These include the two proposed by the Argonne National Laboratory, namely Hearthfire Reference Concepts 2 and 3; the RF linear accelerator proposed by the Brookhaven National Laboratory; and the Induction Linac System advanced by the Lawrence Berkeley Laboratory. It is shown that accelerator systems utilizing rapid cycling synchrotrons are the least attractive drivers unless the efficiency of this component is sufficiently improved. Using a power cost-formula that accounts for the accelerator operating cost it appears on the basis of available data that only one driver might fall within the economically acceptable range of producing electric power at 4 cents a kilowatt hour but only if certain optimistic conditions are met.

Introduction

The use of heavy ions in the implosion of Deuterium-Tritium pellets as a potential approach to fusion power has in recent years received added attention due to several physical considerations. When contrasted with other inertial confinement schemes, especially those utilizing relativistic electron beams, heavy ions provide distinct advantages the most cited of which are⁽¹⁾:

i) higher stopping power, ii) negligible bremsstrahlung thereby reducing or perhaps eliminating preheat problems, iii) very little scattering of beam ions in the target, hence virtually no "reflection" losses of ion beam energy, and iv) higher energy deposition near the end of the range for normal incidence on target surfaces. Large ion energies, perhaps in the tens of GeV will however be required⁽²⁾ to ignite the thermonuclear microexplosions and for that reason special attention is being directed to the design of reliable, efficient high energy accelerators that could serve as drivers for ion beam fusion power reactors.

Several such drivers have been proposed to accelerate multiply charged (e.g., Uranium or Xenon) heavy ions to energies of the order of 20-30 GeV. The Argonne National Laboratory has proposed several designs⁽³⁾ of which the Hearthfire Reference Concepts 1 and 3 make use of a rapid cycling synchrotron system while the Reference Concept 2 totally eliminates the utilization of synchrotrons. The Brookhaven National Laboratory, on the other hand, has proposed the use of an RF Linear Accelerator⁽⁴⁾ to produce a beam of 20 GeV ions at a current of 160 mA, while the Lawrence Berkeley Laboratory has put forth an Induction Linac System which accelerates Uranium ions to about 26 GeV.

In this paper an evaluation of these drivers will be made from the point of view of an overall system analysis of a power plant that utilizes ion beam-pellet fusion reactors. Parametric analysis is carried out to assess the impact of the major components of each driver on the overall performance of the system, and a preliminary cost analysis using available data is performed to evaluate the economic potential of these drivers.

Systems Analysis

We consider the standard power flow diagram for the whole power plant shown in Figure 1. Since only average power values are considered for all the components in this analysis the diagram in question will also represent an energy flow diagram for the system. An energy W_s is supplied to the accelerator whose efficiency is denoted by η_{ACC} from which a beam of ions is delivered to the pellet which we characterize by a gain Q , and an absorption or a coupling efficiency η_A . For a D-T pellet whose fusion products include alpha particles the fraction of fusion energy released as charged particles which may be directly converted is denoted by α^* . Such conversion takes place at an efficiency of η_{DC} . The major portion of the fusion energy is converted via a primary thermal converter operating at an efficiency of η_{TH1} , although a secondary thermal converter operating at an efficiency of η_{TH2} has been included to assess the effect on the overall performance of the system of waste heat recovery from the accelerator. The gross energy from the plant is denoted by W_G , while the circulating and net energies are given by W_C and W_N , respectively. The portion of the energy consumption relative to W_s due to the auxiliary system is denoted by "a" which typically has a value of 5%⁽⁶⁾.

Using the power flow diagram shown in Figure 1, we write energy conservation relations across each plant component and obtain an expression for the plant efficiency η which we can put in the form⁽⁷⁾

$$\eta = \frac{(Q - Q_C)}{Q} \eta_E^* \quad (1)$$

where Q is the pellet gain, and Q_C is the "critical" pellet gain which corresponds to the value of Q when the plant's net electrical energy output W_N is equal to zero. It is given by

$$Q_C = \frac{1+a - \eta_{TH2}(1-\eta_{ACC})}{\eta_A \eta_{ACC} \eta_E^*} \quad (2)$$

with η_E^* being the efficiency by which fusion energy is converted into electricity or

$$\eta_E^* = \eta_{TH1} + \alpha^* (\eta_{DC} - \eta_{TH1}) \quad (3)$$

The circulating energy ratio, C , can be written conveniently in terms of familiar variables:

$$C = \frac{W_C}{W_N} = \frac{(1+a)}{(Q-Q_C) \eta_A \eta_{ACC} \eta_E^*} \quad (4)$$

We now introduce two additional system figures of merit which are independent of Q . They are Q^* and $\eta(Q^*)$ which represent respectively the pellet gain and system efficiency when $C = 1$. The way these parameters change with the efficiency and gain of the various system components can yield information regarding the role of the key components in certain ranges of system parameter space. These variables are given by

$$Q^* = \frac{2(1+a) - \eta_{TH2}(1-\eta_{ACC})}{\eta_A \eta_{ACC} \eta_E^*} \quad (5)$$

and

$$\eta(Q^*) = \frac{(1+a) \eta_E^*}{2(1+a) - \eta_{TH2}(1-\eta_{ACC})} \quad (6)$$

It might be noted that for $\eta_{TH2} = \eta_E^*$ the plant efficiency $\eta(Q^*)$ is independent of the accelerator efficiency. In spite of this independence η_{ACC} must be positive or the values of Q^* will be unphysical. Moreover, it might be seen that $\eta(Q^*)$ has a higher value when η_E^* exceeds η_{TH2} than it has when the opposite is true.

In order to compute the above system parameters we must first obtain the accelerator efficiency and for that we refer to Figure 2 which shows a block diagram of a driver with n components. The efficiency of such a driver is computed from the gains and efficiencies of the individual components. The gain of a component is defined to be the beam energy output divided by the beam energy input, while the efficiency is set equal to the beam output divided by the total energy input.

Figure 2. Accelerator Power Flow Diagram

Using energy conservation relations we can readily write for a system with n components connected in series:

$$W_S \eta_{ACC} = W_1 \eta_1 G_2 G_3 \dots G_n \quad (7)$$

where W_S is the source energy, W_1 is the energy input to the first component whose efficiency is η_1 , and G_n is the gain of the n th component. Noting that

$$W_1 + W_2 + W_3 + \dots W_n = W_S$$

or

$$\frac{W_1}{W_S} + \frac{W_2}{W_S} + \dots \frac{W_n}{W_S} = 1 \quad (8)$$

then the first term in Eq. (8) can be readily replaced by its equivalent from Eq. (7). Moreover, the efficiency of the second component can be expressed as

$$\eta_2 = \frac{W_1 \eta_1 G_2}{W_1 \eta_1 + W_2}$$

which can be further written as

$$\eta_1 (G_2 - \eta_2) \frac{W_1}{W_S} = \eta_2 \frac{W_2}{W_S} \quad (9)$$

Similar equations can be obtained for the remaining components which when combined with Eq. (8) constitute a set of linear algebraic equations in the variables $\frac{W_1}{W_S}, \dots, \frac{W_n}{W_S}$. These equations are then solved for $\frac{W_1}{W_S}$ which when inserted in Eq. (7) will yield the desired quantity, namely η_{ACC} . Some of the drivers we will consider employ more than one unit of each of several components e.g., 4 rebuncher rings or 16 storage rings etc., but these added components do not affect the efficiency of the driver as computed above since the efficiency of a system of parallel components is the same of that of an individual member.

Various Driver Designs

We focus our attention in this study on three drivers proposed by the Argonne National Laboratory, the Brookhaven National Laboratory, and the Lawrence Berkeley Laboratory. As a reference we shall use Argonne's Hearthfire Reference Concept #3 whose major components include a 550 MV Linac, eight 60 Hz synchrotrons, four matching rings, 16 storage rings, and 24 final beam lines and lenses. The power flow diagram for this accelerator is shown in Figure 3, and its basic parameters as obtained from Ref. 3 are displayed in Table 1 where it is observed that the efficiency of this driver is about 0.267. Since many of the components shown in Table 1 are common to other drivers the gains and efficiencies given for these components will be used in assessing the performance of the other drivers.

Table 1
Parameters of Hearthfire #3

<u>Component</u>	<u>Efficiency</u>	<u>Gain</u>
Ion Source	-	-
Low Beta Linac	0.40	-
Strippers	0.15	0.2
Linac	0.40	400
Debuncher	0.90	1.0
Synchrotron	0.40	4.05
Rebuncher Rings	0.90	1.0
Rotator	0.90	1.0
Storage Rings	0.80	0.89
<u>Transport and focus</u>	<u>0.90</u>	1.0
Accelerator	0.267	

By contrast, the Hearthfire Reference Concept #2 of Argonne displayed in Figure 4 completely eliminates the use of synchrotrons and relies essentially on Linacs to accelerate the ions to high energies. The same can be said of the Brookhaven design shown in Figure 5. Several drift tubes along with a Linear Induction Accelerator characterize the Lawrence Berkeley Laboratory's driver schematically displayed in Figure 6. Acceleration of the beam occurs in the low voltage accelerator and in the Induction Accelerator although the latter is mainly responsible for the high energy ion produced by this driver.

The efficiency of each of these drivers is then utilized in the systems analysis to ascertain its impact (as well as that of its major components) on the overall performance of the power pro-

ducing system. The following typical values for the remaining components of Figure 1 are used to carry out the analysis:

$\eta_A = 0.80$, $\eta_{TH1} = 0.40$, $a = 0.05$, $\eta_{DC} = 0.70$, $\alpha^* = 0.20$. We have chosen to ignore the second thermal converter and have thus taken $\eta_{TH2} = 0$.

Results

Before assessing each of the above drivers we find it useful to first examine the impact of the pellet parameters on the overall performance of the system. Using the parameters in Table 1 as the reference case, we note from Figure 7 that the plant efficiency rises rapidly with increasing Q (pellet gain) values up to about $Q = 90$ after which the value of η remains virtually constant. The figure shows that an η of about 36% is obtained at Q of about 50 and that doubling the Q value results in increasing η to about 40% only. Since large Q values are quite difficult to attain it appears on the basis of these results that only modest Q values are needed to produce a plant efficiency comparable to those of conventional power plants.

The effect of the coupling or deposition efficiency η_A is illustrated in Figure 8 which shows the variation of the plant efficiency with the accelerator efficiency at a fixed Q value of 50. We note that at a fixed value of η_{ACC} the value of η increases with increasing η_A but the increase is not dramatic past η_A of about 80%. Since, as pointed out in the introduction, one of the major advantages of using heavy ions for imploding pellets is the high deposition efficiency, Figure 8 reveals that large values of

η_A are needed at low accelerator efficiencies but the enhancement in the plant efficiency due to large values of η_A at higher accelerator efficiencies is indeed minimal.

In the specific case of Hearthfire #3 which employs synchrotrons to accelerate the ions to high energies we see from Figure 9 that large synchrotron efficiencies are required to produce modest driver efficiencies. In fact we note that a Linac efficiency of 40% and a synchrotron efficiency of 40% are needed to produce a driver efficiency of 26%. Figure 9 also reveals that at large synchrotron efficiencies the overall accelerator efficiency can be further enhanced by increasing the Linac efficiencies. Such enhancement is much less dramatic at low synchrotron efficiencies where the accelerator efficiency is almost completely dominated by that of the synchrotron.

When the synchrotron is replaced by the heavy ion Linac as the major accelerating component, the Hearthfire 3 is effectively transformed into the Hearthfire 2 design shown in Figure 4. For this driver the low beta linacs have very little effect on the accelerator efficiency as seen from Figure 10 where the accelerator efficiency is plotted against the Linac efficiency. We note that a Linac efficiency exceeding 60% is needed to produce a driver efficiency of about 26% regardless of how efficient the low beta linacs are. The role of the other components in the performance of this driver is illustrated in Figure 11-13 where we note that an increase in the focus gain and efficiency leads to better driver efficiency although in the latter case saturation is reached at about 40% efficiency especially at low Linac efficiencies. Similar behavior occurs in the case of varying the storage ring efficiency

as depicted in Figure 13. It should be noted that the impact of these components on the performance of the driver is common to all the drivers considered in this study whenever such components are utilized.

The Brookhaven driver shown in Figure 5 is not drastically different from Hearthfire 2 in that it also employs a heavy ion linac along with some low beta linacs such as the Wideroe and Alvarez linacs to accelerate the particles to the desired energies. The dependence of the driver efficiency on the focus and transport gain and efficiency is similar to that of Hearthfire 2 discussed above but the dependence on the Linac efficiency seems to be more dramatic as revealed by Figure 14. We note from this figure that a Linac efficiency of 40% results in an accelerator efficiency of about 32% whereas the same efficiency produced an accelerator efficiency of about 20% in Hearthfire 2. Figure 14 also shows that no tangible enhancement in the driver efficiency results from increasing the efficiencies of the low beta components. It appears on the basis of these figures and underlying data that the Brookhaven accelerator is a more efficient driver than the Hearthfire 2 which shares with it the major accelerating components.

In the Berkeley design the main ion acceleration is performed by the linear induction accelerator and the drift tubes play a role not too dissimilar from the low beta components of the previous two drivers. Here again the dependence on the focus and transport gain and efficiency is similar to the other drivers, while the impact of the drift tubes on the driver efficiency is almost negligible. This last observation may be seen from Figure 15 where we also note that the increase in the overall accelerator

efficiency with that of the induction accelerator is perhaps more dramatic than that of the Brookhaven design. Using the same reference point of 40% efficiency for the main component we find that in the Berkeley design this leads to a driver efficiency of near 40%. Although the efficiency of an accelerator is a strong measure of its performance as a driver in an ion beam-fusion reactor, it is by no means the only criterion. Cost is a very decisive factor, and for this reason we have carried out a cost assessment of the three drivers using a power cost formula which is commonly used in such studies. It must be kept in mind that, since no power-producing fusion reactor has been built, some of the parameters employed in this analysis will be based on data available from the fission reactor industry. Moreover, whenever such data does not appear to be well established, a parametric analysis is carried out to identify the regions of interest. The formula in question can be expressed in the form

$$\text{Power Cost} \left(\frac{\$}{\text{kWe-hr}} \right) = \frac{\text{operating cost} \left(\frac{\$}{\text{yr}} \right) + \text{fuel cost} \left(\frac{\$}{\text{yr}} \right) + \text{return on capital} \left(\frac{\$}{\text{yr}} \right)}{\frac{8776 \text{ hr}}{\text{yr}} \times \text{availability} \times \text{plant output} (\text{KW}_{\text{th}}) \times \eta_{\text{plant}} \left(\frac{\text{kWe}}{\text{KW}_{\text{th}}} \right)}$$

where the individual terms are defined as follows:

Operating cost = accelerator operating cost + plant remainder
operating cost

It has been pointed out⁽⁴⁾ that the accelerator operating cost represents 10% of the accelerator capital cost. Since it is not clear what fraction of the plant capital cost does the accelerator

capital cost represent we will assume that this fraction is comparable to that in typical light water fission reactors, namely about 25%.⁽⁹⁾ For the purposes of comparison however we shall consider cases where this fraction assumes the values 20%, 25%, and 40%. It is also shown in Ref. 4 that the plant remainder operating cost represents 5% of the plant remainder capital cost and we will utilize this figure in the present analysis. Moreover we will take the plant remainder capital cost to be about 60% of the plant capital consistent once again with light water reactors.⁽⁹⁾ We will take the fuel cost to be negligible and assume that the return on capital is 15% of the plant capital cost.

The final quantity that must be specified before applying the above equation to the drivers under consideration is the plant availability. A generally accepted value for this parameter is 70%⁽⁹⁾, but in the interest of comparison we shall also examine cases with more optimistic values such as 80% and 95%. For the first case we shall take the following values:

$$\begin{aligned}
 \text{Accelerator operating cost} &= 0.04 \text{ plant cap cost} \\
 \text{plant remainder op cost} &= 0.03 \text{ plant cap cost} \\
 \text{fuel cost} &= 0 \\
 \text{return on capital} &= 15\% \text{ plant cap cost} \\
 \text{availability} &= 95\% \\
 \frac{\text{plant cap cost}}{KW_{th}} &= \frac{\text{power cost} \times 8776 \times 0.95 \times \eta}{0.04 + 0.03 + 0.15}
 \end{aligned}$$

Since

$$\frac{\text{Acc. cap cost}}{KW_{th}} = \frac{0.40 \text{ plant cap cost}}{KW_{th}}$$

we can, using the plant capital cost and the plant efficiency establish whether each of the above drivers falls in the acceptable

cost range if the price of electricity is taken to be 4 cents per KWe-hr⁽⁴⁾. It is interesting to note that conceptually-designed fusion power plants fall in the range of 1500-2200 \$/KWe^(10,11), so using the above relations and an η value of 40% we find that the range for the accelerator capital cost 240-352 \$/KWth. For the purposes of comparison and illustration we choose a pellet gain factor Q of 70 for all plants and find that

- a) Hearthfire #2, at 1 MJ per pulse, 20 pulses per second and a capital cost of 513×10^6 dollars⁽⁸⁾ yields an accelerator cost of 366 \$/KW_{th}.
- b) The Brookhaven Driver at 10 MJ per pulse, 15 pulses per second and a capital cost of 1420×10^6 dollars⁽⁸⁾ yields an accelerator cost of 135 \$/KWth.
- c) The Berkeley Induction system at 1 MJ/pulse, and one pulse per second and a capital cost of 394×10^6 dollars⁽⁸⁾ yields 5630 \$/KWth. The pulse rate used in this calculation is indeed low so if the pulse rate can be increased to 10 or 20 per second then the accelerator cost will drop to 563 \$/KWth and 281 \$/KWth respectively.

The above cost comparison is vividly displayed in Figure 16 where the maximum allowable accelerator cost per KWth based on the above assumptions is plotted against the accelerator efficiency for several values of pellet gains. On the basis of the figures reported above it appears that the Brookhaven Driver is the only one that falls in the acceptable cost range. The figure also confirms the earlier statement that a pellet gain of 50 seems to be adequate unless the accelerator efficiency drops to unacceptably low values.

Since some of the parameters (e.g., availability and the accelerator capital cost as a fraction of the plant capital cost) employed in obtaining the above results may appear questionable we have recalculated the results of Figure 16 by changing the values of these parameters in accordance with the values given in Table 2, leaving the other parameters unchanged.

Table 2

Values of Availability and Accelerator Cost Fraction

Case	Availability	Accelerator cost percentage (% total plant cost)
I	0.70	0.20
II	0.70	0.25
III	0.80	0.25
IV	0.80	0.20

The results are shown in Figures 17-20. We now observe that none of the drivers considered in this study fall in the acceptable cost range. These figures also reveal the impact that these parameters have on the maximum allowable accelerator cost per kilowatt of thermal power. By keeping the accelerator cost percentage the same and increasing the availability from 70% to 80% Figure 19 shows a marked improvement in the maximum allowable cost over that given in Figure 18 where the availability is 70%. When comparing Figure 19 with 20, which share the same availability, it is readily seen that the maximum allowable accelerator cost is higher when the accelerator cost percentage is higher. These same results can also be seen when Figures 17 and 18 are compared.

Driver Component Sensitivity

Since each of the drivers examined in this study is complex and consisting of many components it is useful to assess the role of each component in the overall performance of the driver. Specifically it is important to know the sensitivity of the accelerator efficiency with respect to the efficiency and gain of each of the components that make up the accelerator. In the interest of deriving generalized formulas that can be applied to any of the drivers we first calculate the sensitivity coefficients for the generalized accelerator shown in Figure 21 which we take to consist of nine major parts. If a particular driver to which these results will be applied does not contain a particular component then the generalized results can be directly extended by simply setting the efficiency and the gain of the missing component equal to unity. In deciding on the generalized accelerator we were, of course, guided by the designs of the various drivers analyzed in this study.

The generalized accelerator efficiency can be written as

$$\eta_{ACC} = \frac{x}{y} = \frac{GN}{y} \quad (10)$$

where $G = G_9 \dots G_2$ and $N = \eta_1 \dots \eta_9$ is the product of all the efficiencies. The quantity y is given by

$$y \equiv \frac{N}{\eta_1} + (G_2 - \eta_2) \frac{N}{\eta_2} + (G_3 - \eta_3) G_2 \frac{N}{\eta_3} + (G_4 - \eta_4) G_3 G_2 \frac{N}{\eta_4} + \dots + (G_9 - \eta_9) G_8 \dots G_2 \frac{N}{\eta_9} \quad (11)$$

If we now define

$$\begin{aligned} D_1 &= \frac{N}{\eta_1}, \quad D_2 = G_2 \frac{N}{\eta_2}, \quad D_3 = -\frac{\eta_2}{G_2} D_2 \\ D_{16} &= G_9 \dots G_2 \frac{N}{\eta_6}, \quad D_{17} = -\frac{\eta_9}{G_9} D_{16} \end{aligned} \quad (12)$$

then Eq. (10) can be put in the form

$$\eta_{ACC} = \frac{GN}{\sum_{i=1}^{17} D_i} \quad (13)$$

With this form we can proceed to derive the generalized sensitivity coefficients. We note that if all the η_j 's and G_j 's are fixed except for η_i then we can write

$$\Delta \eta_{ACC} = \frac{\partial \eta_{ACC}}{\partial \eta_i} \Delta \eta_i \quad (14)$$

which upon dividing by η_{ACC} and multiplying the right hand side by η_i/η_i becomes

$$\frac{\Delta \eta_{ACC}}{\eta_{ACC}} = S_{\eta_i} \frac{\Delta \eta_i}{\eta_i}$$

where we have introduced

$$S_{\eta_i} = \frac{\partial \eta_{ACC}}{\partial \eta_i} \frac{\eta_i}{\eta_{ACC}} \quad (15)$$

From Eq. (13) we can write

$$\frac{\partial \eta_{ACC}}{\partial \eta_i} = - \frac{x}{y^2} \frac{\partial y}{\partial \eta_i} + \frac{1}{y} \frac{\partial x}{\partial \eta_i}$$

and noting that

$$\frac{\partial x}{\partial \eta_i} = \frac{x}{\eta_i}$$

$$\frac{\partial y}{\partial \eta_i} = \frac{y^{-D_{2i-2}}}{\eta_i} \quad \text{for } i > 1$$

$$= \frac{y^{-D_i}}{\eta_i} \quad \text{for } i = 1$$

then it could readily be shown that the efficiency sensitivity coefficient for the i^{th} component is

$$S_{\eta_i} = \frac{D_{2i-2}}{\sum_{i=1}^{17} D_i} \quad \text{for } i > 1 \quad (16)$$

$$= \frac{D_i}{\sum_{i=1}^{17} D_i} \quad \text{for } i = 1$$

In a similar way we find that if all the η_j 's and G_j 's are fixed except for $G_i (i>1)$ we can write

$$S_{G_i} = \frac{\sum_{j=1}^{17} D_j - \sum_{j=2i-2}^{17} D_j + D_{2i-1}}{\sum_{j=1}^{17} D_j} \quad (17)$$

which is the gain sensitivity coefficient for the j^{th} component.

We now apply these results to Hearthfire #2 given in Reference 3. It must be noted from the above derivation, however, that the efficiencies and gains of all the components must be known in order to calculate the sensitivity coefficients of any one component. Since all the components of Hearthfire #2 except the Beam Delay Ring and Beam Compressor are also components of Hearthfire #3, the values for the latter as cited in Table 1 can be used for the common components. For the Beam Delay Ring Reference 3 gives 0.74 as a gain, and using an efficiency ratio for this component of $\eta = 0.9$ G (consistent with most of the data in Table 1) we can use $\eta = 0.67$. We will also assume that the Beam Compressor of Hearthfire #2 has the same efficiency and gain as the Rebuncher Rings of Hearthfire #3 i.e., $\eta = 0.90$ and $G = 1.0$. With these values we can calculate the sensitivity coefficients for this driver and the results are shown in Table 3. It might be noted that these calculated values agree quite well with the sensitivities deduced directly from the figures!

Table 3
Sensitivity Coefficients for Hearthfire #2

Component	S	S_G
Low Beta Linac	0.0105	-
Ion Stippers	0.0056	0.0063
Heavy Ion Linac	0.839	0.0111
Beam Debuncher	0.373	0.515
Beam Delay Ring	0.371	0.552
Beam Storage Ring	0.276	0.675
Beam Compressor	0.246	0.730
Transport and Focus	0.246	0.754

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PLANT POWER BALANCE

Fig. 1 PLANT POWER BALANCE

HEARTFIRE REFERENCE CONCEPT #3

ACCELERATOR POWER BALANCE

3

Fig. 3

ACCELERATOR POWER BALANCE

HEARTHFIRE REFERENCE CONCEPT #2

ACCELERATOR POWER BALANCE

Figure 4.

BROOKHAVEN REFERENCE CONCEPT

ACCELERATOR POWER BALANCE

Figure 5.

BERKELEY
ACCELERATOR POWER BALANCE

Figure 6.

Fig. 7

PLANT EFFICIENCY VS PELLETT GAIN

PLANT EFFICIENCY VERSUS ACCELERATOR EFFICIENCY FOR Q VALUE OF 50 AND DEPOSITION EFFICIENCIES OF .6, .8, 1.

Fig. 8 PLANT EFFICIENCY VS ACCELERATOR EFFICIENCY FOR VARIOUS DEPOSITION EFFICIENCIES

ACCELERATOR EFFICIENCY VERSUS
SYNCHROTRON EFFICIENCY
FOR LINAC EFFICIENCIES OF .2 , .4 , AND .6

Fig. 9 EFFECT OF LINAC EFFICIENCY ON ACCELERATOR EFFICIENCY

ACCELERATOR EFFICIENCY VERSUS
LINAC EFFICIENCY FOR
LOW BETA EFFICIENCIES OF .4,.2,.1

Figure 10.

ACCELERATOR EFFICIENCY VERSUS FOCUS GAIN

Figure 11.

ACCELERATOR EFFICIENCY VERSUS
FOCUS EFFICIENCY FOR
LINAC EFFICIENCIES OF .4,.2,.1

Figure 12.

ACCELERATOR EFFICIENCY VERSUS
STORAGE RING EFFICIENCY FOR
LINAC EFFICIENCIES OF .4,.2,.1

Figure 13.

BRC

ACCELERATOR EFFICIENCY VERSUS
HEAVY_ION_LINAC EFFICIENCY FOR
WIDEROE EFFICIENCIES OF .4,.2,.1

Figure 14.

LBL
ACCELERATOR EFFICIENCY VERSUS
INDUCTION ACC. EFFICIENCY FOR
DRIFT TUBE2 EFF.S OF .4,.2,.1

Figure 15.

ACCELERATOR COST(\$/KWT) VERSUS
ACCELERATOR EFFICIENCY
FOR ELECTRICITY AT \$.04/KWE-HR

Figure 16.

MAXIMUM ALLOWABLE ACCELERATOR COST

Figure 17. Case I, Table 2

MAXIMUM ALLOWABLE ACCELERATOR COST

Figure 18. Case II, Table 2

MAXIMUM ALLOWABLE ACCELERATOR COST

Figure 19. Case III, Table 2

MAXIMUM ALLOWABLE ACCELERATOR COST

Figure 20. Case IV, Table 2

Figure 21. Generalized Accelerator

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