UCRL-ID-132991

Scoping the Parameter Space for Demo and Engineering Test Facility (ETF)

Wayne R. Meier

January 19, 1999

Lawrence Livermore National Laboratory

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information
P.O. Box 62, Oak Ridge, TN 37831
Prices available from (615) 576-8401, FTS 626-8401

Available to the public from the
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Rd.,
Springfield, VA 22161

ICF Applications Group
Mail Stop L-446
Phone: 422-8536, Fax: 422-7390
Email: wmeier@llnl.gov

Memorandum

Aug. 23, 1998
Jan. 12, 1999, Rev. 1
WRM-98-012

To: R. Bangerter, S. Bodner, M. Campbell, H. Powell
Copies: J. Barnard, A. Faltens, A. Friedman, E. Lee, J. Lindl, G. Logan, C. Marshall, R. Moir, S. Payne, J. Perkins
From: Wayne Meier
Subject: Scoping the Parameter Space for Demo and ETF

Introduction

In our IFE development plan, we have set a goal of building an Engineering Test Facility (ETF) for a total cost of \$2B and a Demo for \$3B. In Mike Campbell's presentation at Madison, we included a viewgraph with an example Demo that had 80 to 250 MW_e of net power and showed a plausible argument that it could cost less than \$3B. In this memo, I examine the design space for the Demo and then briefly for the ETF. Instead of attempting to estimate the costs of the drivers, I pose the question in a way to define R&D goals:

As a function of key design and performance parameters, how much can the driver cost if the total facility cost is limited to the specified goal?

The design parameters examined for the Demo included target gain, driver energy, driver efficiency, and net power output. For the ETF, the design parameters are target gain, driver energy, and target yield. The resulting graphs of allowable driver cost determine the goals that the driver R&D programs must seek to meet.

In this memo, I will refer to the figures contained in the attached Mathcad document, which also includes all the assumptions.

Parameter Ranges Considered

Target Gain

Figure 1 (p. 2 of Mathcad attachment) shows the target gain curves used in the analysis. The laser curves were fit to those shown in Fig. 10 of Ref. 1. While the isentrope parameter α is used as the designator, the range of gains from $\alpha = 1$ to 3 can be thought of as way to represent uncertainty and different designs (e.g., effects of 2D calculations, improvements from laser zooming, use of indirect drive, etc.). There are two curves for the heavy ion driver. The base case has the same functional form and shape as the $\alpha = 3$ curve, but is degraded by 10% so that it passes through the Tabak/Callahan-Miller distributed radiator point design ($G = 73$ at $E = 5.9$ MJ).

Preliminary results by Callahan-Miller show that gains higher than the base case are possible using close-coupled target designs. A second heavy-ion target gain curve fits results for the close-coupled target designs.

Driver Energy

The range from 1-10 MJ was examined, but most interesting cases are less than 5 MJ.

Driver Efficiencies

Driver efficiencies ranged from 5 to 10% for lasers and 15 to 30% for accelerators.

Net Power

I looked at three cases: 100, 300 and 500 MW_e.

Costs for Non-driver Components.

I've made very simple costing assumptions for the cost of Demo and ETF facility costs derived from previous power plant studies.[2,3] Fusion components (chamber, target factory, heat transfer system, and buildings) are costed at \$1000/kW_t (same as Wisconsin presentation). This is about 1.5 times upper end of plant costs from IFE power plant studies. Power generation equipment (turbine plant equipment, electrical plant equipment and associated buildings) cost scaling is taken from the Osiris study (most conservative case); it is equal to \$550/kW_e at 1100 MW_e and scales as (total electric power)$^{0.6}$.

Results

Allowable Laser Driver Cost for Different Net Powers

Figure 4 (p. 8) shows the allowable laser driver total cost (expressed in 100's of dollars per joule) as a function driver energy for net powers of 100, 300 and 500 MW_e assuming a driver efficiency of 7% and the $\alpha = 2$ gain curve. (Note that "total cost" includes all the indirect costs; allowable **direct** costs would be about a factor of two lower.) The smaller the net power of the Demo, the higher the allowable driver cost to stay within the \$3B limit since less money is spent on the plant components. On the other hand, the higher the net power of the Demo, the closer its cost of electricity (COE) will be to levels that can be scaled convincingly to competitive energy. The curves show peaks in allowed driver cost at 1.6, 2.0 and ~3 MJ for P_{net} = 100, 300, and 500 MW_e, respectively. At driver energies below these peaks, the target gain decreases rapidly and recirculating power increases (see Fig. 2, p. 5) resulting in a large plant size and cost to produce the desired net power; this leaves less money for the driver. Beyond the peaks, there is no benefit, in terms of increased gain and reduced recirculating power, of building a larger laser. (This is true unless the economy of scale for the driver is such that the \$/J is falling faster than the allowable \$/J with increasing driver energy.)

Don't be too quick to conclude that we want a small net power for the Demo. The resulting cost of electricity is 59.3, 19.8 and 11.9 cents/kW_eh for the 100, 300 and 500 MWe cases, respectively. Since the Demo will be the last government funded facility and must demonstrate the economic attractiveness for IF power, this is an important consideration. In the future, I'll address the potential of multi-unit plants sharing a single driver to show the potential of these designs.

Figure 5 (p. 9) is the same as Fig. 4 except I have added the rep-rate required to generate the specified net power. This curve can be used to answer the question of what driver energy is required if rep-rate is limited and what the allowable driver cost is under such a constraint. For example, the 300 MW_e case has a peak allowable driver cost of \$640/J at a driver energy of 2 MJ (~ \$1.3B total) corresponding to a rep-rate of 8.6 Hz. If the rep-rate was limited to 5 Hz, a 2.5 MJ driver would be needed to generate 300 MWe, and the allowable cost would be \$600/J (\$1.5B total).

Allowable Laser Driver Cost for Different Target Gain Curves

Figure 6 (p. 10) is similar to Fig. 5 except it shows results for different target gain curves with P_{net} fixed at 300 MW_e. If $\alpha = 1$ target performance could be achieved, a 5 Hz, 300 MW_e Demo could be built using a 1.5 MJ driver costing up to \$1100/J total. With $\alpha = 3$ type performance, the allowable driver cost is about \$275/J over the range of 3.5 to 4.5 MJ (7 to 4 Hz).

Allowable Laser Driver Cost for Different Driver Efficiencies

Figure 7 (p. 11) shows the impact of varying the laser efficiency while holding the net power constant at 300 MW_e. As expected, higher efficiency lasers can be more expensive under the assumption of a fixed total Demo cost since the recirculating power is lower, and thus the size and cost of the plant is smaller. Conversely, lower efficiency lasers are allowed if the cost per joule is low enough.

Allowable HIB Driver Cost for Different Net Powers

Figure 8 (p. 12) shows the allowable heavy ion driver cost and rep-rate as a function of driver energy for net powers of 100, 300, and 500 MW_e assuming the base case gain curve and a driver efficiency of 20%. The trends are very similar to the laser driver (see Fig. 5) with the 300 MW_e case also peaking near 2 MJ. The allowable costs are somewhat higher than the laser case in Fig. 5, indicating that the higher driver efficiency more than offsets the lower target gain. The target yield at a given energy is significantly lower however (see Fig. 3, p. 6) so the rep-rate required for a specified net power is higher than in the laser case (17.7 Hz vs. 8.6 Hz at E = 2 MJ). If the rep-rate for the 300 MW_e case is limited to 5 Hz, a 3.4 MJ driver would be needed with a maximum total cost of \$510/J, significantly lower than the \$730/J allowed at 2 MJ.

Allowable HIB Driver Cost for Different Gain Curves

Figure 9 (p. 13) shows the effect of using the close-coupled HIB target gain curve. The trends are similar to the laser case (e.g., going from $\alpha = 2$ to $\alpha = 1$ in Fig. 6.). The benefit of the higher gain curve decreases with increasing driver energy; at 2 MJ, an additional \$200/J would be allowed, while at 3 MJ, the additional allowance is less than \$70/J. With the close-coupled target, the rep-rate for 300 MW_e falls to 5 Hz at a driver energy of ~ 1.7 MJ corresponding to an allowable driver cost of \$1100/J.

Allowable HIB Driver Cost for Different Driver Efficiencies

Figure 10 (p. 14) shows the sensitivity of the results to variations in the HIB driver efficiency over the range of 15 to 30%. As with the laser, the sensitivity to changes in driver efficiency is greater at lower driver energy where the gain is lower. At 2 MJ, increasing the driver efficiency from 20 to 30% would allow an additional ~$110/J, while at 3 MJ the additional allowance is only ~ $40/J.

ETF Results

The ETF is characterized more by the yield per shot than the power, although it will test average power operation at least for limited periods of time. The ETF is assumed to dump its thermal power and therefore does not require the electric power generating equipment and associated costs as with the Demo. Recall that the total cost goal here is $2 B. Here again we ask, for a given size ETF, what is the allowable driver cost?

Figure 11 (p. 15) shows driver energy required to achieve a specified yield for the different laser and HIB gain curves. In previous studies, we showed that small scale chamber test could be done at the ~ 30 MJ yield level.[4] This would require a driver energy of 0.8 to 2 MJ depending on the type of driver and gain curve.

Figure 12 (p. 16) shows the allowable ETF driver cost as a function of the desired yield for the various drivers and gain curves. At 30 MJ, the allowable total costs are quite large (> $1000/J). Even at 60 MJ, the allowable costs are all > $500/J. This bodes well for the possibility that future ETF designs can meet the < $2B TPC limit.

Conclusions

A broad range of parameters have been examined for the Demo and ETF with the idea of determining what is needed in terms of driver cost in order to meet the cost goals that we've expressed. This memo is intended to initiate discussion on the subject and should be considered preliminary. At this point, nothing is set in stone and additional case can easily be run.

Some of the questions we need to address are:

1) How close does the Demo have to come to being economically competitive, and will replicating these small chambers in a multi-unit plant get us close enough?
2) What power levels allow reasonable cost goals for the drivers?
3) Multi-unit power plants will help meet the COE and total development cost goals through upgrades. What are the beam transport, beam switchyard, and final optics costs per chamber allowed to support multiple chambers?

References

1. S. E. Bodner et al., 'Direct-Drive Laser Fusion; Status and Prospects," NRL report, NRL/MR/6730-98-8113 (March 13, 1998)
2. W. R. Meier, et al., "Osiris and Sombrero Inertial Fusion Power Plant Designs, W.J. Schafer Associates report, WJSA-92-01, DOE/ER/54100-1 (1992)
3. R. W. Moir, "Improvements to the HYLIFE-II Inertial Fusion Power Plant Design," *Fusion Technol.* 26 (1994) 1169-1177.
4. W. R. Meier and W. J. Hogan, "An Integrated Test Facility for Inertial Fusion Energy Using Heavy Ion Drivers," Proc. 15 IEEE/NPSS Sym. on Fusion Engineering (Hyannis, MA, Oct. 11-15, 1993) 0-7803-1412-3, p. 1001 (1994).

Demo Parameter Study
8/22/98
1/12/99 Revised to include close-coupled target gain for heavy ion driver
Wayne Meier, LLNL
(925) 422-8536 / wmeier@llnl.gov

Set input assumptions for Demo plant:

$fa := 0.04$ Auxiliary power fraction (excludes driver power requirements)

$M := 1.1$ Energy multiplication factor (typical factor)

$\varepsilon := 0.43$ Thermal conversion efficiency (Typical of HYLIFE-II and Osiris)

Target Gain
Gain curves for $\alpha = 1, 2, 3$ for lasers fit to Bodner et al. APS paper in 1-2 MJ range.
Base case heavy ion gain curve goes through Tabak, Callahan-Miller design (E = 5.9 MJ, Y = 430 MJ). A second HIB case is for close-coupled target designs.

Laser curves for $\alpha = 1, 2, 3$:

$G1(E) := 70 + 130 \cdot \ln(E)$ $\quad G1(2) = 160.1$

$G2(E) := 16 + 78 \cdot \ln(E)$ $\quad G2(2) = 70.1$

$G3(E) := 2.5 + 44 \cdot \ln(E)$ $\quad G3(2) = 33$

HIB driver curves (base case and close-coupled target design):

$G4(E) := 0.9 \cdot G3(E)$ $\quad G4(5.9) = 72.5$

$G5(E) := 59.6 + 61.5 \cdot \ln(E)$ $\quad G5(3.3) = 133$

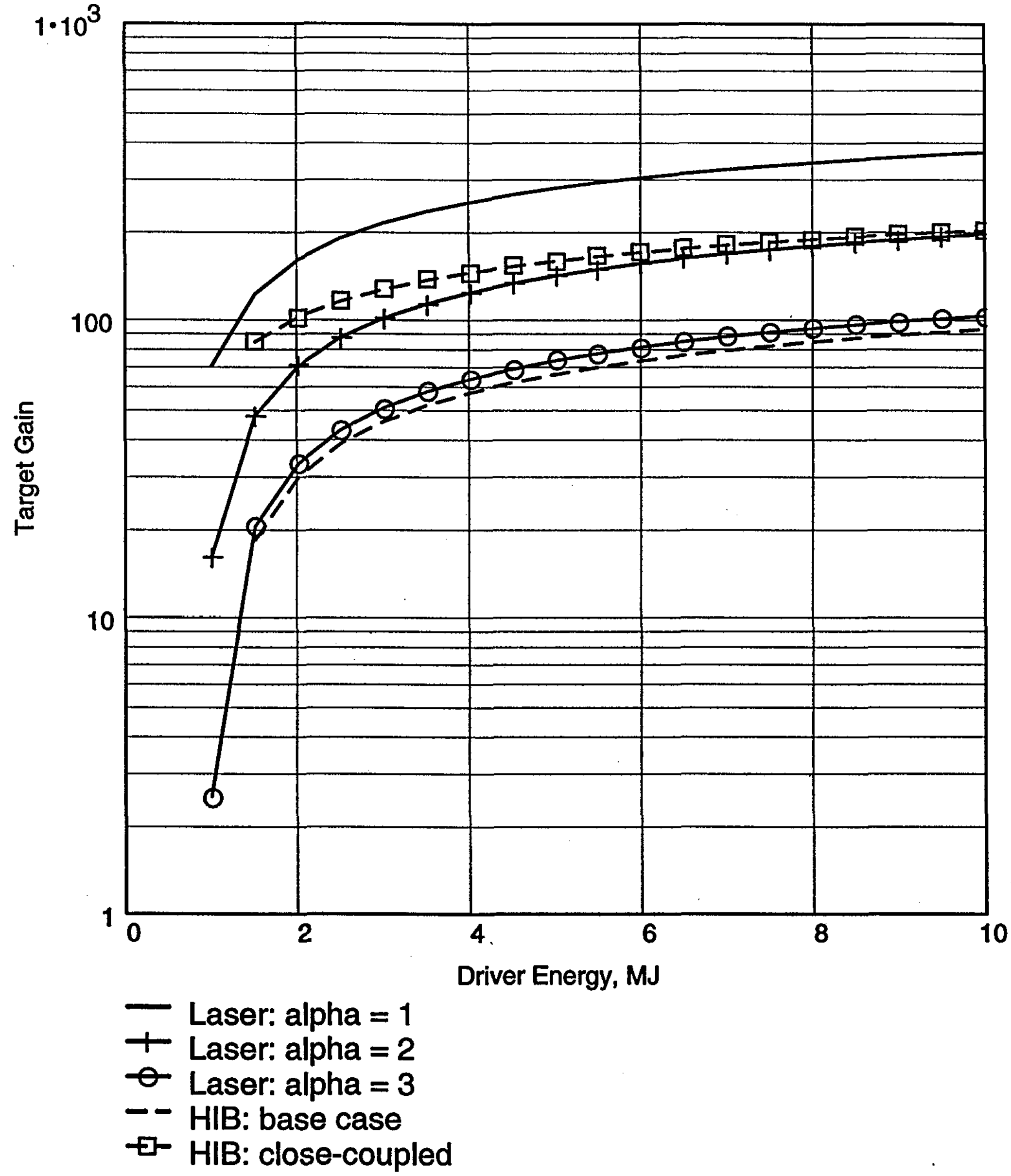
Select a gain curve:
a = 1 --> $\alpha = 1$
a = 2 --> $\alpha = 2$
a = 3 --> $\alpha = 3$
a = 4 --> HIB base case
a = 5 --> HIB close-coupled target design

$Ga(a,E) := \text{if}(a<2, G1(E), (\text{if}(a<3, G2(E), (\text{if}(a<4, G3(E), G4(E))))))$

$G(a,E) := \text{if}(a<5, Ga(a,E), G5(E))$

Define plot ranges: $E1 := 1, 1.5 .. 10$ $\quad E4 := 1.5, 2.0 .. 10$ $\quad E5 := 2.5, 3 .. 10$

Fig. 1. Target gain curves



The following variables are used:

a = target gain designator
E = driver energy, MJ
η = driver efficiency
Pn = net power, MWe

Define some parameters for example calculations:

Driver energy, MJ

$Eo := 2$

Laser efficiencies

$\eta5 := 0.05$

$\eta7 := 0.07$

$\eta10 := 0.10$

Heavy ion driver efficiencies

$\eta15 := 0.15$

$\eta20 := 0.20$

$\eta30 := 0.30$

Net electric power, MWe

$Pno := 300$

When net power is specified, rep-rate is a calculated value (normal mode).
If rep-rate is fixed, net power will vary.
Example rep-rate for fixed rep-rate case, Hz

$RRo := 5$

Thermal power, MWt

$$Pt(a,E,\eta,Pn) := \frac{Pn}{\varepsilon\cdot\left(1 - fa - \frac{1}{\eta\cdot G(a,E)\cdot M\cdot\varepsilon}\right)}$$

Example calculation:

$Pt(2,Eo,\eta7,Pno) = 1319$

If fixed rep-rate, use following

$Pt(a,E,\eta,Pn) := RRo\cdot E\cdot G(a,E)\cdot M$▫

Rep-rate, Hz

$$RR(a,E,\eta,Pn) := \frac{Pt(a,E,\eta,Pn)}{E \cdot G(a,E) \cdot M}$$

$RR(2,Eo,\eta 7,Pno) = 8.56$

Yield, MJ

$$Y(a,E) := E \cdot G(a,E)$$

$Y(2,Eo) = 140.1$

Fusion power, MW

$$Pf(a,E,\eta,Pn) := Y(a,E) \cdot RR(a,E,\eta,Pn)$$

$Pf(2,Eo,\eta 7,Pno) = 1199.1$

Gross (total) electric power, MWe

$$Pg(a,E,\eta,Pn) := Pt(a,E,\eta,Pn) \cdot \varepsilon$$

$Pg(2,Eo,\eta 7,Pno) = 567.2$

Auxiliary power, MWe

$$Paux(a,E,\eta,Pn) := fa \cdot Pg(a,E,\eta,Pn)$$

$Paux(2,Eo,\eta 7,Pno) = 22.7$

Driver power, MWe

$$Pd(a,E,\eta,Pn) := E \cdot \frac{RR(a,E,\eta,Pn)}{\eta}$$

$Pd(2,Eo,\eta 7,Pno) = 244.5$

Calculated net power, MWe (needed when rep-rate is fixed)

$$Pnet(a,E,\eta,Pn) := Pg(a,E,\eta,Pn) - Pd(a,E,\eta,Pn) - Paux(a,E,\eta,Pn)$$

$Pnet(2,Eo,\eta 7,Pno) = 300$

Recirculating power fraction for driver

$$RPF(a,E,\eta,Pn) := \frac{Pd(a,E,\eta,Pn)}{Pg(a,E,\eta,Pn)}$$

$RPF(2,Eo,\eta 7,Pno) = 0.43$

Fig. 2. Driver recirculating power fraction
vs. driver energy for different gain curves
Laser efficiency = 7%
HIB efficiency = 20%

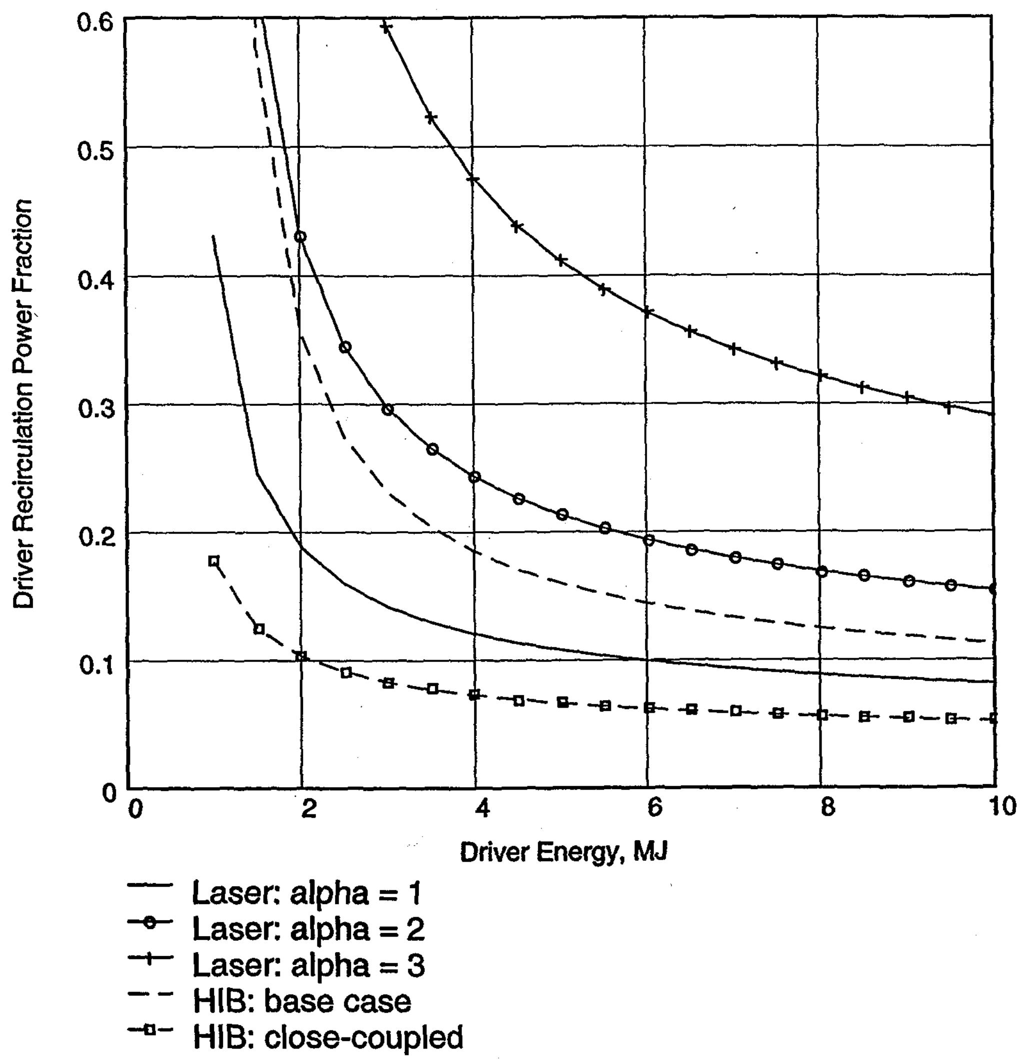
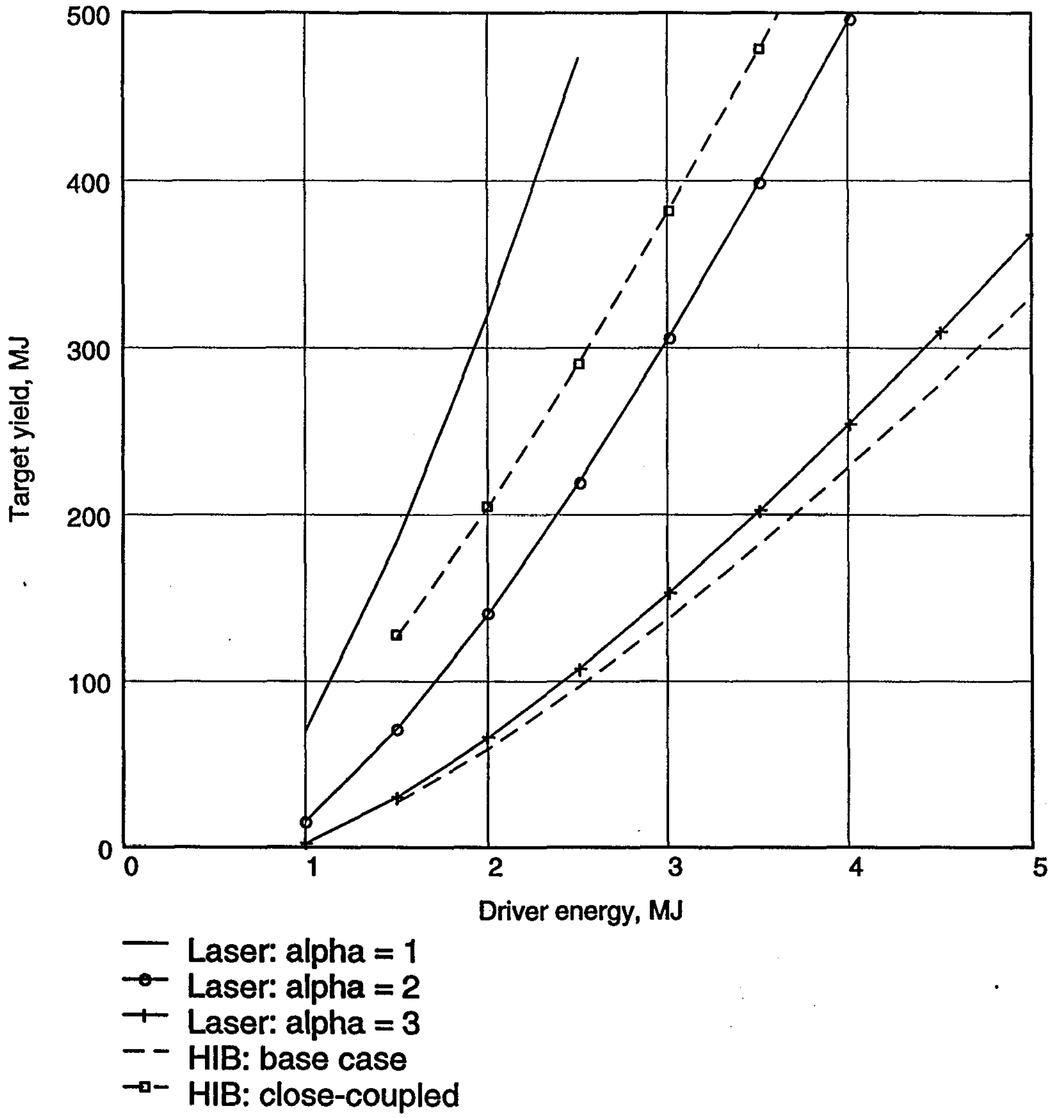


Fig. 3. Yield vs. driver energy for various gain curves



Fusion Component Costs.
Includes chamber, target factory, main heat transfer system, buildings
Total cost = \$1000/kWt = \$$10^6$/ MWt = 1.5 times upper end of costs from power plant studies

Unit cost, \$/ MWt

$$UCfc := 10^6$$

Total cost, \$

$$Cfc(a,E,\eta,Pn) := UCfc \cdot Pt(a,E,\eta,Pn) \qquad Cfc(2,Eo,\eta 7,Pno) = 1.32 \cdot 10^9$$

Turbine and Electric Plant Equipment (plus associated buildings).
\$550/kWe at 1100 MWe. Scales as Power$^{0.6}$

Cost at 1100 MWe, \$

$$Cteo := 0.55 \cdot 10^6 \cdot 1100$$

$$Cte(a,E,\eta,Pn) := Cteo \cdot \left(\frac{Pg(a,E,\eta,Pn)}{1100}\right)^{0.6} \qquad Cte(2,Eo,\eta 7,Pno) = 4.07 \cdot 10^8$$

Allowable driver cost is \$3B minus the other costs, \$

$$Cdallow(a,E,\eta,Pn) := 3 \cdot 10^9 - Cfc(a,E,\eta,Pn) - Cte(a,E,\eta,Pn)$$

$$Cdallow(2,Eo,\eta 7,Pno) = 1.27 \cdot 10^9$$

Total allowed cost for driver (express in 100's \$/J)

$$Cdpj(a,E,\eta,Pn) := \frac{Cdallow(a,E,\eta,Pn)}{E \cdot 10^6} \cdot 0.01$$

Define plot range
$Eg := 1.4, 1.6 .. 5$

Fig. 4. Allowable laser driver total cost (100's $/J) for:
Total Demo cost = $3B
Target $\alpha = 2$
Driver efficiency = 7%
Net power =100, 300, 500 MWe

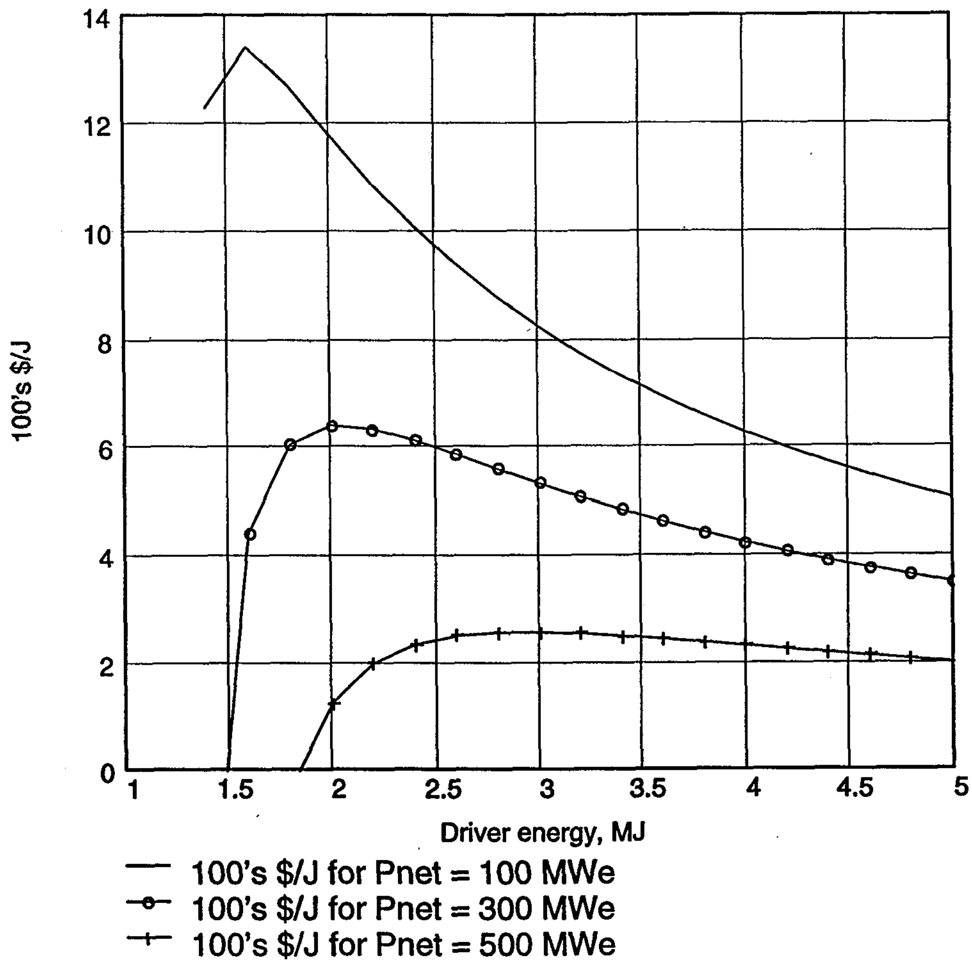
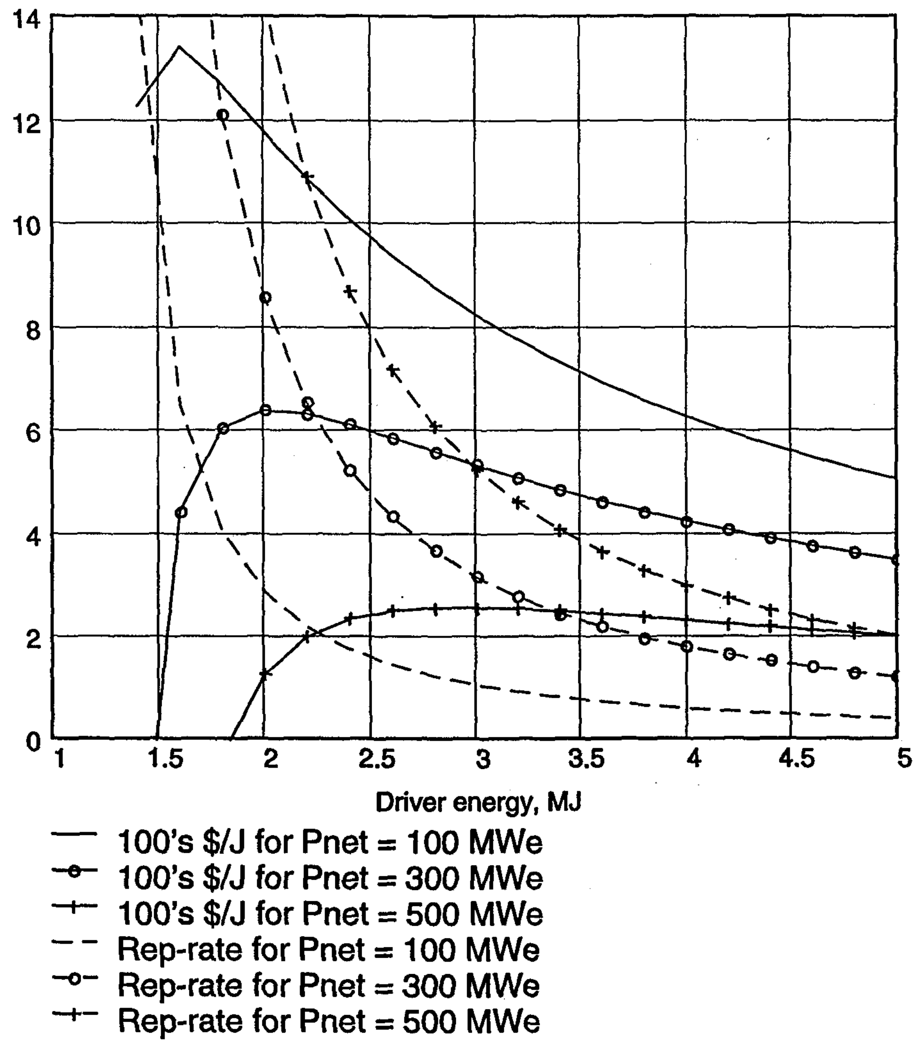


Fig. 5. Allowable laser driver total cost (100's $/J) and rep-rate (Hz) for:
Total Demo cost = $3B
Target $\alpha = 2$
Driver efficiency = 7%
Net power =100, 300, 500 MWe



E3 := 2.2, 2.4 .. 5

Fig. 6. Allowable laser driver total cost (100's $/J) and rep-rate (Hz) for:
Total Demo cost = $3B
Target α = 1, 2, 3
Driver efficiency = 7%
Net power = 300 MWe

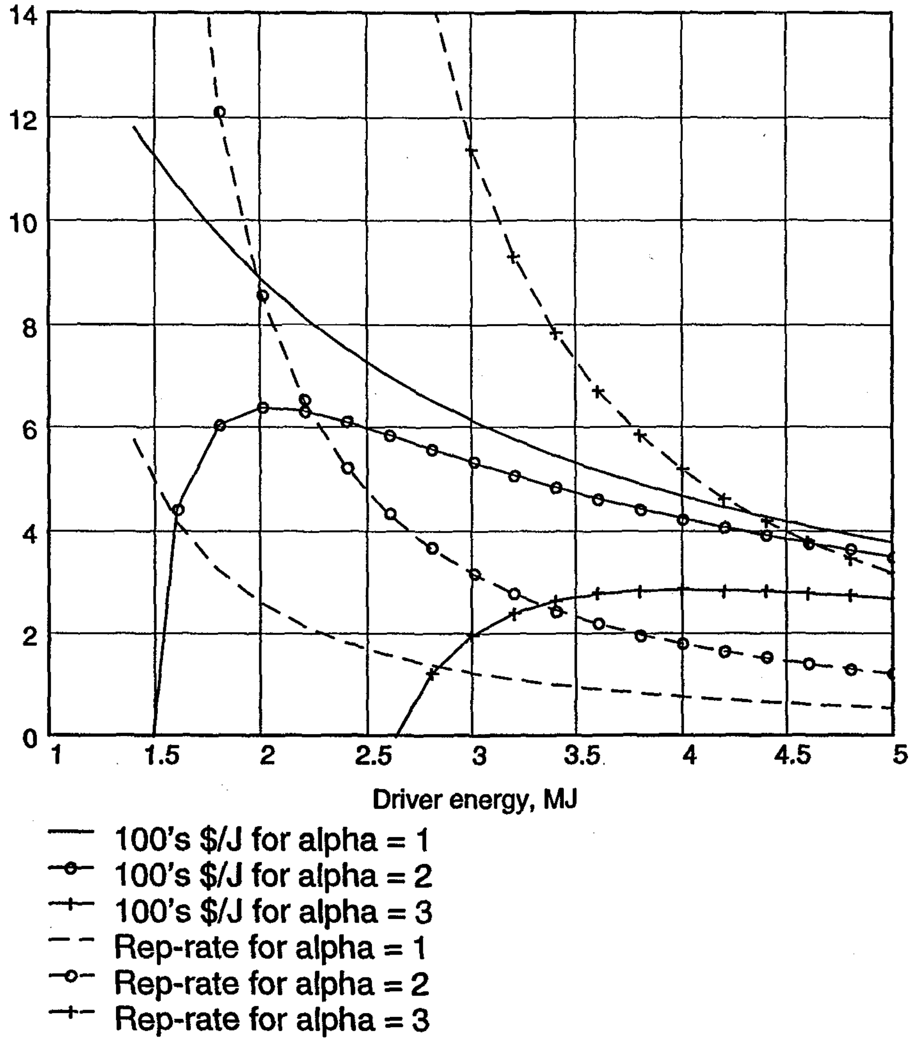
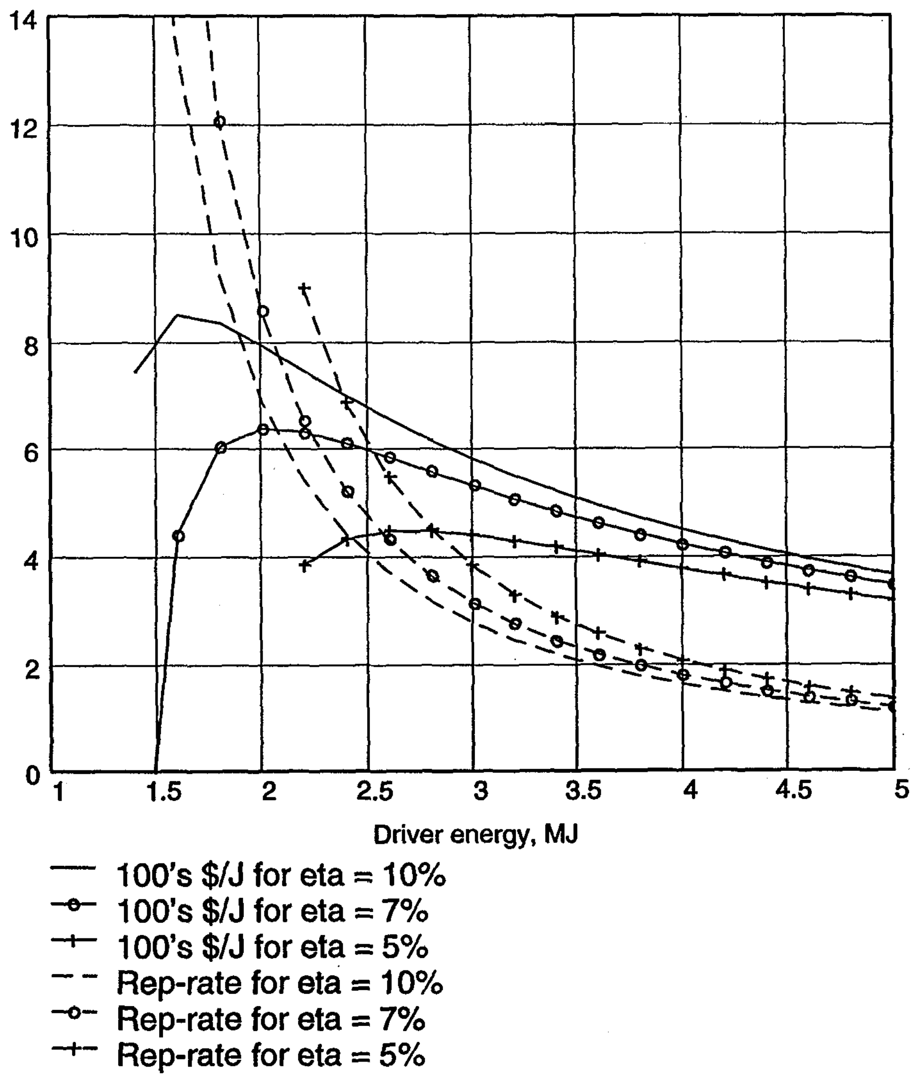


Fig. 7. Allowable laser driver total cost (100's $/J) and rep-rate (Hz) for:
Total Demo cost = $3B
Target $\alpha = 2$
Driver efficiency = 5, 7, 10%
Net power = 300 MWe



E4 := 1.4 , 1.6 .. 5

Fig. 8. Allowable HIB driver total cost (100's $/J) and rep-rate (Hz) for:
Total Demo cost = $3B
Target = heavy ion base case
Driver efficiency = 20%
Net power = 100, 300, 500 MWe

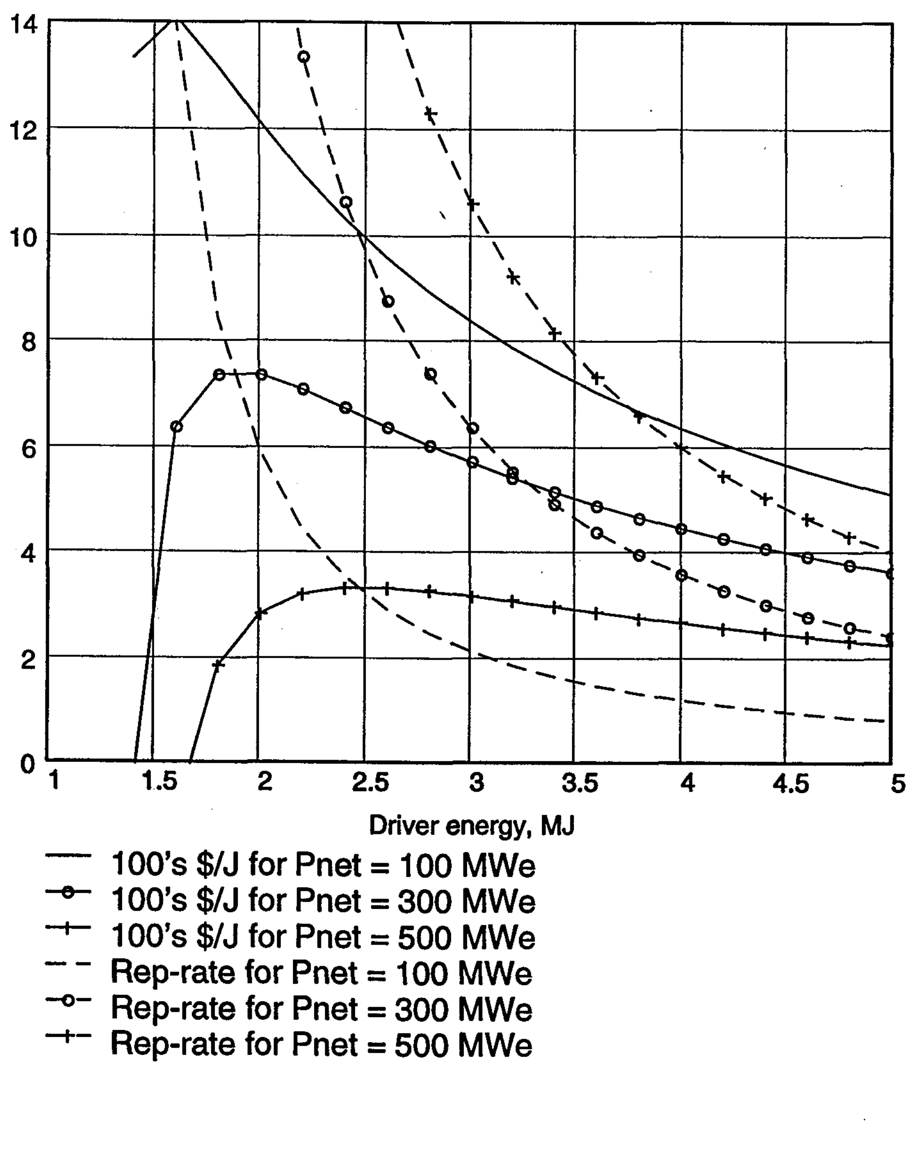


Fig. 9. Allowable HIB driver total cost (100's $/J) and rep-rate (Hz) for:
Total Demo cost = $3B
Target = HIB base case and close-coupled
Driver efficiency = 20%
Net power = 300 MWe

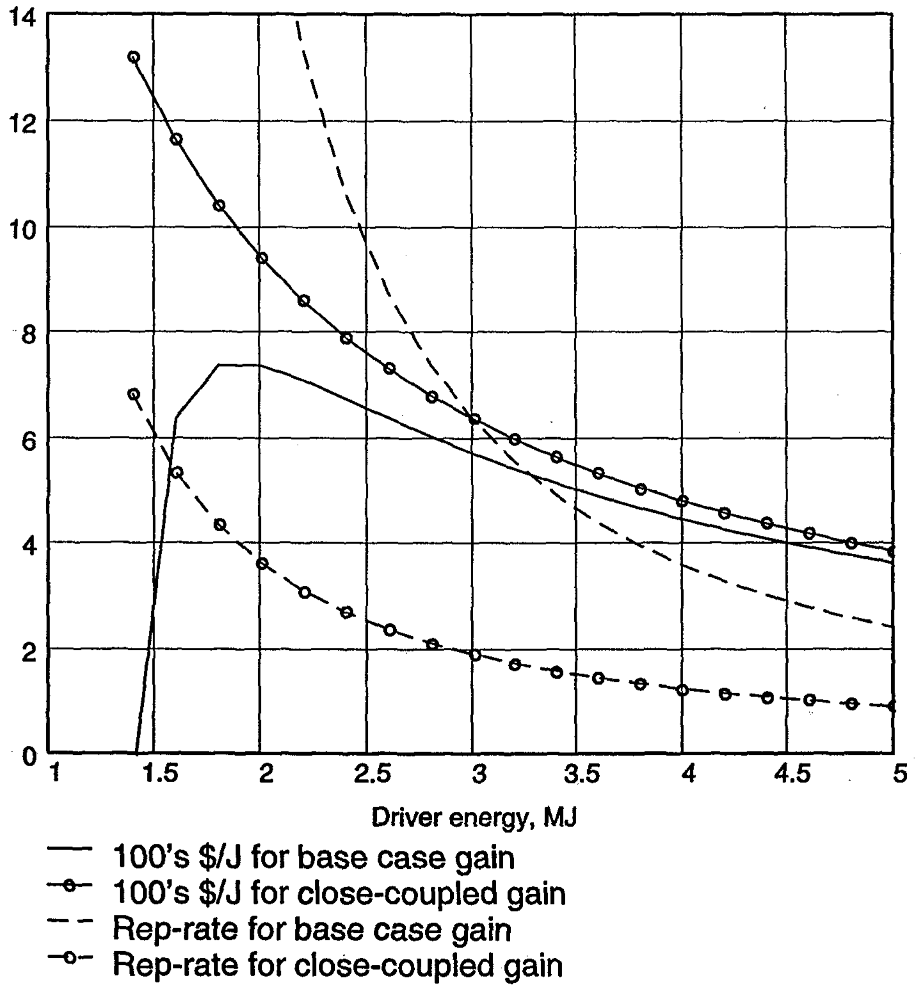
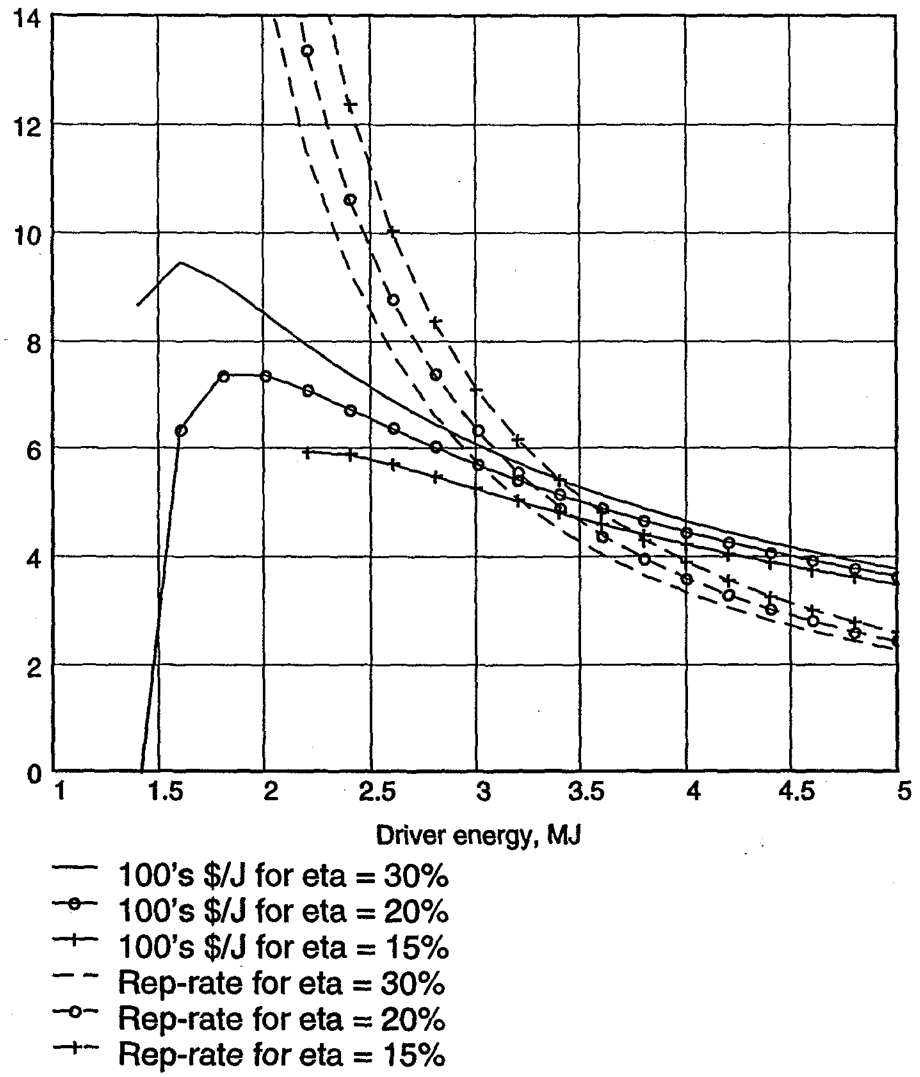


Fig. 10. Allowable HIB driver total cost (100's $/J) and rep-rate (Hz) for:
Total Demo cost = $3B
Target = HIB base case
Driver efficiency = 15, 20, 30%
Net power = 300 MWe



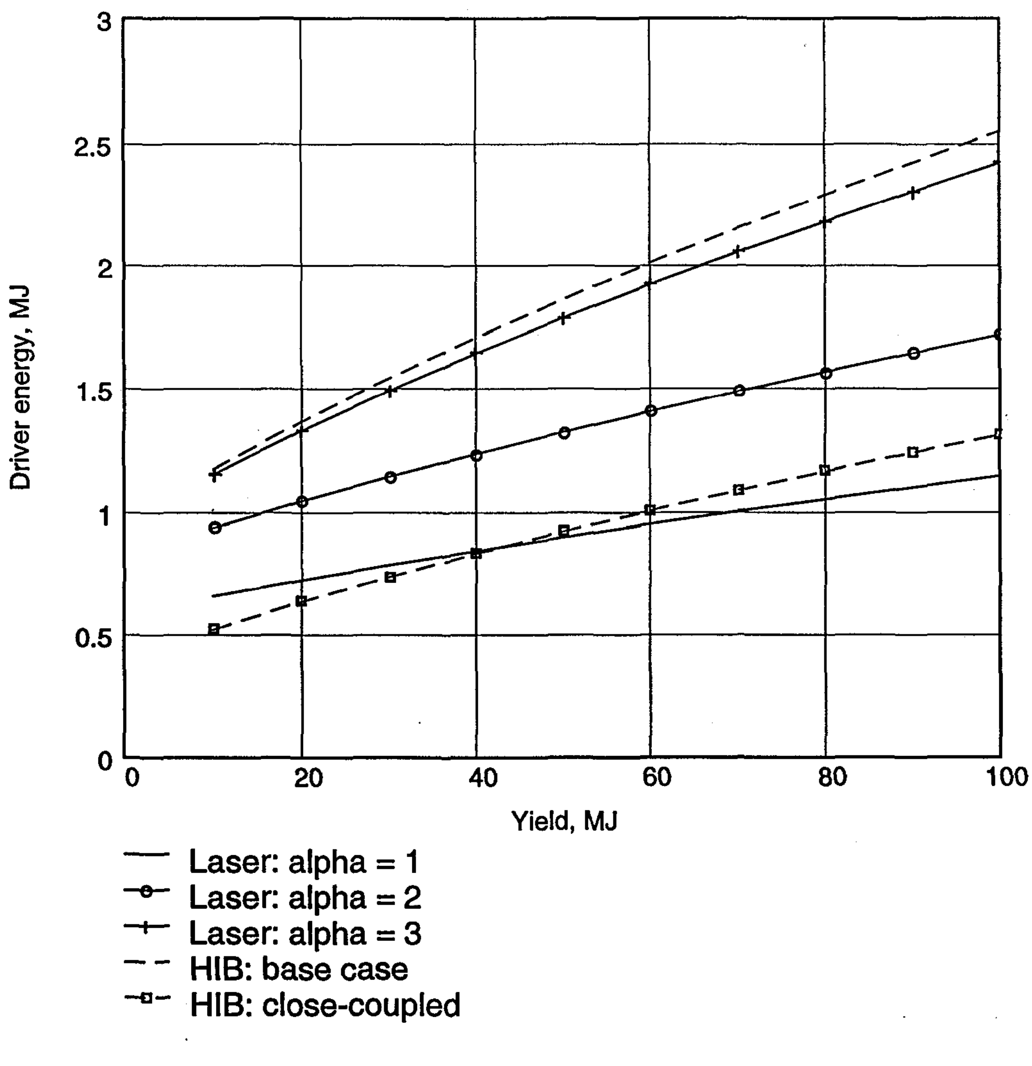
Find the driver energy needed for a particular yield goal for the ETF.

Egv := 2 guess value

Eyg(a, Ygoal) := root(Y(a, Egv) - Ygoal, Egv)

Yg := 10, 20 .. 100

Fig. 11. Driver energy required for a specified ETF yield goal



To find allowable driver cost for ETF, assume the following:
- Total cost = $2 B
- Max rep-rate = 10 Hz so thermal power = 10*Ygoal
- No electric power production
- Fusion chamber and heat transfer components costed at $1000/kWt = $$10^6$/MWt

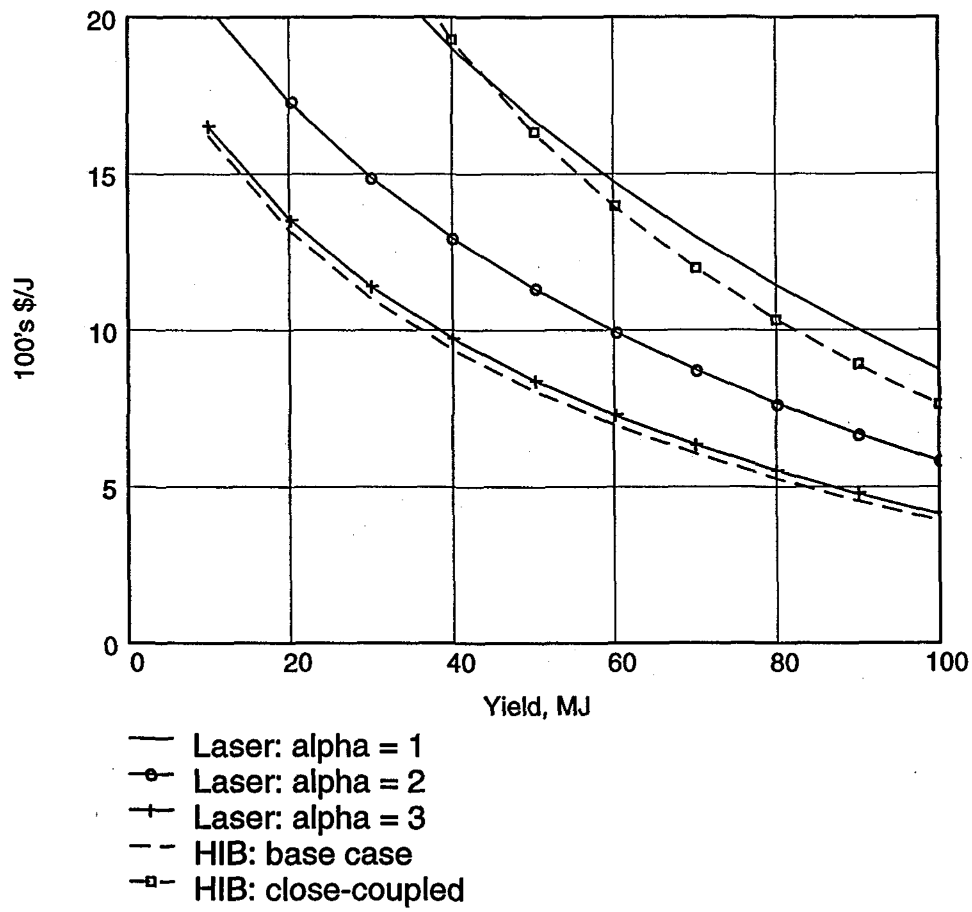
Total allowable ETF driver cost

$CdETF(a, Ygoal) := 2\cdot 10^9 - UCfc\cdot 10\cdot Ygoal$ $\qquad$ $CdETF(2, 50) = 1.5\cdot 10^9$

Allowable driver cost expressed in 100's $/J

$Cdpjy(a, Ygoal) := \frac{CdETF(a, Ygoal)}{Eyg(a, Ygoal)\cdot 10^6}\cdot 0.01$ $\qquad$ $Cdpjy(2, 50) = 11.34$

Fig. 12. ETF driver allowable total cost (100's $/J) vs. yield per pulse for various target gain curves (assumes 10 Hz maximum rep-rate)



Cost of Electricity Calculation for Demo

Total Capital Cost, \$M (assumed goal)

$TCC := 3 \cdot 10^3$

Annual O&M Cost, \$M (assume fixed and not dependent on plant size for Demo. (This is about 2x normal power plant scaling at the 500 MWe size.)

$OM := 100$

Ignore fuel costs and decommissioning costs

Constant Dollar Cost of Electricity, cents/kWeh
0.0966 = constant dollar fixed charge rate, 1/yr
0.75 = capacity factor
8760 = hours per year
10^5 = conversion of \$M to cents and MWe to kWe

$$COE(Pn) := \left(\frac{0.0966 \cdot TCC + OM}{8760 \cdot 0.75 \cdot Pn}\right) \cdot 10^5$$

$COE(100) = 59.33$

$COE(300) = 19.78$

$COE(500) = 11.87$

$COE(800) = 7.42$