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A New Heavy-Ion-Beam Drive Model for the SAFIRE Code

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A NEW HEAVY-ION-BEAM DRIVER MODEL FOR THE SAFIRE CODE

ABSTRACT

The heavy-ion-beam driver model that was developed by McDonnell Douglas Astronautics Corporation as part of the Heavy Ion Fusion System Assessment study has been incorporated into the SAFIRE code. The model calculates the cost and performance of an induction linear accelerator and the beam transport systems required to deliver the beam to the fusion chamber. The results are used within the SAFIRE code for economic evaluation of inertial confinement fusion electric power plants. This report briefly describes the subroutines that make up the driver model, defines the variables that were added to the SAFIRE code, and gives an example of the output for a calculation using the new driver model.

INTRODUCTION

As part of the Heavy Ion Fusion System Assessment study, McDonnell Douglas Astronautics Corporation (MDAC) developed a detailed model for a heavy-ion-beam (HIB) driver for an inertial confinement fusion (ICF) electric power plant¹. The model contains cost and performance scaling relationships for an induction linear accelerator (linac) and the beam transport systems required to deliver the beam to the fusion chamber. The scaling relationships for the accelerator were benchmarked to results from Lawrence Berkeley Lab's LIACEP code². The MDAC HIB driver model has been incorporated into the SAFIRE code, which was developed to carry out economic analyses of ICF electric power plants. The SAFIRE code is describe in detail in Refs. 3 and 4. This report, which serves as a supplement to the previous SAFIRE reports, gives a brief description of the subroutines that make up the MDAC HIB driver model, defines the variables that were added to the SAFIRE code, and gives an example of the output for a calculation using the new driver model.

SUBROUTINES AND FUNCTIONS

The MDAC HIB driver model includes the following subroutines and functions: HIBMD, BTRANS, LINAC, DRCOST, F4, F5, G46TERM, and G30TERM. The original coding was done by D. Driemeyer, L. Waganer, and D. Zuckerman of MDAC and supplied to Lawrence Livermore National Laboratory for incorporation in the SAFIRE code. The input and output of each subroutine and function are listed below.

SUBROUTINE HIBMD

This subroutine is the entry point for the MDAC HIB driver model calculations. Several variables which are calculated or set at other points in the SAFIRE code are used as inputs to HIBMD. Some of these variables are simply redefined in HIBMD to minimize the revisions needed in the rest of the driver model subroutines. MAIN in SAFIRE calls HIBMD, and HIBMD calls BTRANS.

INPUT:

CRADUS	Chamber radius (m)
ETA	Target gain parameter (use ETA = 0.005, 0.01, 0.02, or 0.04)
NCAVIT	Number of chambers per reactor unit
NDRIVE	Number of drivers per plant
NUNIT	Number of reactor units per plant
RPRATE	Pulse repetition rate per chamber (Hz)
TENERG	Driver energy on target (MJ)

OUTPUT:

DRIVEN	Number of drivers per plant = NDRIVE
GAMMAH	Gain curve parameter = $(RSPOT)^{3/2} \times RANGE = ETA$

NCAVT	Number of chambers per plant = NCAVIT x NUNIT
RCAVT	Chamber radius (m) = CRADUS
RNGMAX	Maximum allowable ion range (g/cm^2)
RNGMIN	Minimum allowable ion range (g/cm^2)
RRATE	Driver pulse repetition rate (Hz) = (NCAVT x RPRATE) / DRIVEN

SUBROUTINE BTRANS

This subroutine calculates the beam transport characteristics. BTRANS calls LINAC, DRCOST, F4, and F5.

INPUT:

AION	Ion mass (amu)
BPOLE	Pole tip field strength in final focus magnet (T)
EION	Ion energy (GeV)
GAMMAH	Gain curve parameter
IACCNF	Accelerator cost, efficiency, and length normalization factor selection flag
IFIXEI	Iteration flag to find EION that gives minimum cost
IPRNT	Printout control flag
IRRAD	Pellet irradiation scheme flag
NBEAMH	Number of beams in the accelerator
NCAVT	Number of reactor chambers per plant
RCAVT	Chamber radius (m)
RNGMAX	Maximum allowable ion range (g/cm^2)
RNGMIN	Minimum allowable ion range (g/cm^2) Note: RNGMIN & RNGMAX are not used for IFIXEI = 1
RRATE	Driver pulse repetition rate (Hz)
TAUP	Beam pulse length (s)
TENERG	Driver energy on target (MJ)
XLEN	Distance between first wall and final focus magnet (m)
ZTARG	Average atomic number of target surface layer

OUTPUT:

ALPHAH	$RSPOT/(TENERG)^{(1/3)}$ for Lindl-Mark targets
BCTOT	Total beam current (A)
BCLET	Beam current per beamlet (A)
BCLETMAX	Most restrictive current limit (A)
BGAM	Beta times gamma, where beta is the ion speed relative to the speed of light, and gamma is $[1 / \text{SQRT}(1 - \text{beta}^2)]$
DLEN	Delay line length for double-pulse configuration (m)
EION	Ion energy (GeV)
EMIT	Emittance in beam transport (microrad-m)
EMITACC	Unnormalized accelerator emittance (microrad-m)
FARAD	Final aperture inner radius (m)
FFLEN	Final focus system length (m)
FLEN	Final focus magnet focal length
FMLEN	Final magnet length (m)
FMRAD	Final magnet radius (m)
FTLEN	Final transport system length (m)
IERR	Error signal flag
ICRIT	Basis for determination of THET 1 = THET not constrained (determined by chamber radius) 2 = THET determined by THMAX 3 = THET determined by allowable EMIT
IMAX	Maximum allowable ion energy (GeV)
IMIN	Minimum allowable ion energy (GeV)
NBFT	Number of beams in final transport
PERV	Beamlet perveance
RANGE	Ion penetration distance in target (g/cm^2)
RSPOT	Beam spot radius (cm)
SYLEN	Switch-yard length for double-pulse configuration (m)
TAUP	Beam pulse length (s)

THET	Final focus convergence angle (rad)
THMAX	Maximum convergence angle based on aberration condition (rad)

SUBROUTINE LINAC

This subroutines calculates the linac cost, efficiency, and length using polynomial fits to LIACEP results. LINAC calls G46TERM and G30TERM.

INPUT:

AION	Ion mass (amu)
EION	Ion energy (GeV)
EMITACC	Unnormalized accelerator emittance (microrad-m)
IACCNF	Accelerator cost, efficiency, and length normalization factor selection flag
NBEAMH	Number of beams in the accelerator
RRATE	Driver pulse repetition rate (Hz)
TENERG	Driver energy on target (MJ)

OUTPUT:

CLINAC	Linac cost based on LIACEP (M\$)
DBLEN	Linac length based on LIACEP (km)
ETADRV	Linac efficiency based on LIACEP (%)
IERR	Error signal flag

SUBROUTINE DRCOST

This subroutine calculates the direct capital cost of the driver.

INPUT:

BRHO	Beam stiffness (T-m)
CLINAC	Linac cost based on LIACEP (M\$)
CNORM	Accelerator cost normalization factor
DBLEN	Linac length based on LIACEP (km)
DLLEN	Delay line length for double-pulse configuration (m)
FFLEN	Final focus system length (m)

FLEN	Final focus magnet focal length
FTLEN	Final transport system length (m)
IACCNF	Accelerator cost, efficiency, and length normalization factor selection flag
IRRAD	Pellet irradiation scheme flag
NBEAMH	Number of beams in the accelerator
NBFT	Number of beams in final transport
PERV	Beamlet perveance
SYLEN	Switch-yard length for double-pulse configuration (m)
THET	Final focus convergence angle (rad)

OUTPUT:

C27	Accelerator subsystem cost (M\$)
C2701	Ion source/preaccelerator cost (M\$)
C2702	Accelerator modules and power supplies cost (M\$)
C2703	Pulse compression system cost (M\$)
C2704	Beam transport system cost (M\$)
C2705	Final focus system cost (M\$)
C2706	Cooling system cost (M\$)
C2707	Accelerator and transport vacuum cost (M\$)
C2708	Driver maintenance equipment cost (M\$)
C2709	Instrumentation and control cost (M\$)
IERR	Error signal flag

FUNCTION F4

This function calculates the ion range as a function of ion energy, ion mass and target effective atomic number.

INPUT:

AION	Ion mass (amu)
EION	Ion energy (GeV)

ZTARG Average atomic number of target surface layer

OUTPUT:

RANGE Ion penetration distance in target (g/cm^2)

FUNCTION F5

This function calculates the ion energy as a function of ion range, ion mass and pellet effective z.

INPUT:

AION Ion mass (amu)

RANGE Ion penetration distance in target (g/cm^2)

ZTARG Average atomic number of target surface layer

OUTPUT:

EION Ion energy (GeV)

SUBROUTINES G46TERM and G30TERM

These subroutines calculate the terms for the 46-term and 30-term accelerator curve fit polynomials.

INPUT:

AION Ion mass (amu)

EION Ion energy (GeV)

EMITACC Unnormalized accelerator emittance (microrad-m)

RRATE Pulse repetition rate of driver (Hz)

TENERG Driver energy on target (MJ)

OUTPUT:

TERM Term of the polynomial

COMMON BLOCK

The following common block was added to the SAFIRE Code.

COMMON / HIB2CB /

AION	Ion mass (amu)
ALPHAH	$RSPOT/(TENERG)^{(1/3)}$ for Lindl-Mark targets
BCLET	Beam current per beamlet (A)
BCTOT	Total beam current (A)
BPOLE	Pole tip field strength in final focus magnet (T)
BPWRSQM	Beam power density (TW/cm^2)
BRHO	Beam stiffness (T-m)
CLINAC	Linac cost based on LIACEP (M\$)
CNORM(4,3)	Array of accelerator normalization data
C27	Accelerator subsystem cost (M\$)
C2701	Ion source/preaccelerator cost (M\$)
C2702	Accelerator modules and power supplies cost (M\$)
C2703	Pulse compression system cost (M\$)
C2704	Beam transport system cost (M\$)
C2705	Final focus system cost (M\$)
C2706	Cooling system cost (M\$)
C2707	Accelerator and transport vacuum cost (M\$)
C2708	Driver maintenance equipment cost (M\$)
C2709	Instrumentation and control cost (M\$)
DBLEN	Linac length based on LIACEP (km)
DELTAH	Beam momentum spread ($\Delta p / \text{mean } p$)
DLEN	Delay line length for double-pulse configuration (m)
EION	Ion energy (GeV)
EMIT	Emitance in beam transport (microrad-m)
EMITACC	Unnormalized accelerator emittance (microrad-m)

EMITMN	Minimum allowable emittance = 15 microrad-m
EMITMX	Maximum allowable emittance = 30 microrad-m
ETADRV	Linac efficiency based on LIACEP (%)
FARAD	Final aperture inner radius (m)
FFLEN	Final focus system length (m)
FLEN	Final focus magnet focal length
FMLEN	Final magnet length (m)
FMRAD	Final magnet radius (m)
FTLEN	Final transport system length (m)
GAMMAH	Gain curve parameter = $(RSPOT)^{3/2} \times RANGE$
IACCNF	Accelerator cost, efficiency, and length normalization factor selection flag
IERR	Error signal flag
IFIXEI	Iteration flag to find EION that gives minimum cost
IPRNT	Printout control flag
IRRAD	Pellet irradiation scheme flag
ICRIT	Basis for determination of THET
NBEAMH	Number of beams in the accelerator
NBFT	Number of beams in final transport
NCAVT	Total number of chambers driven by the HIB driver
PERV	Beamlet perveance
RANGE	Ion penetration distance in target (g/cm^2)
RCAVT	Reactor cavity radius (m)
RCX	Camber radius plus standoff (m)
RHOTRANS	Final transport bend radius (m)
RNGMAX	Maximum allowable range (g/cm^2)
RNGMIN	Minimum allowable range (g/cm^2)
RRATE	Pulse repetition rate of driver (Hz)

RSPOT	Beam spot radius (cm)
SYLEN	Switch-yard length for double-pulse configuration (m)
TAUP	Beam pulse length (s)
THET	Final focus convergence angle (rad)
XLEN	Distance between first wall and final focus magnet (m)
ZTARG	Average atomic number of target surface layer
ZION	Ion charge state

NAMELIST

An additional NAMELIST group called HIB2NL was added to the SAFIRE code. HIB2NL will only be read if IDRIVE in NAMELIST DSYST is set equal to 5. If the following variables are not read in, they will be assigned the default values given in parenthesis.

NAMELIST / HIB2NL /

AION	Ion mass (130 amu)
BPOLE	Pole tip field strength in final focus magnet (1.0 T)
DELTAH	Beam momentum spread (0.001)
EION	Ion energy (8.0 GeV) Note: only an input when IFIXEI = 1, if IFIXEI = 0, EION is an output
IACCNF	Accelerator cost, efficiency, and length normalization factor selection flag: (3) 1 = single pulse, ZION = 1 2 = double pulse, ZION = 3 (set IRRAD = 1) 3 = single pulse, ZION = 3
IFIXEI	Iteration flag to find EION that gives minimum cost: (0) 0 = iterate between IMIN and IMAX 1 = no iteration, must specify EION
IPRNT	Printout control flag: (0) 0 = disable detailed printout 1 = enable detailed printout
IRRAD	Pellet irradiation scheme flag: (2) 1 = single sided (use for IACCNF = 2) 2 = double sided 3 = multi-sided planar (16 beams) 4 = multi-sided fully symmetric (16 beams)
NBEAMH	Number of beams in the accelerator (16) (allowable values: 4, 8, 16)

TAUP	Beam pulse length (14.1 E-9 s)
XLEN	Distance between back of first wall and final focus magnet (2.0 m)
ZTARG	Average atomic number of target surface layer (13.0)

USING THE MDAC HIB DRIVER MODEL

Information on access to the SAFIRE code is contained in Ref. 3. The MDAC HIB driver model is selected by specifying IDRIVE = 5 in NAMELIST DSYST. Note that with this driver model, ETA in NAMELIST CBANDS must be equal to 0.005, 0.01, 0.02, or 0.04. An example input file for the Cascade chamber is shown in Figure 1, and the corresponding output file is shown in Figure 2.

REFERENCES

1. D. S. Zuckerman, D. E. Driemeyer and L. M. Waganer, "An Induction-Linac Heavy Ion Fusion Systems Model," McDonnell Douglas Astronautics Company report (Dec. 1986), to be published in of Fusion Technology.
2. J. Hovingh, "Analysis of an Induction Linac Driver System," Lawrence Berkeley Laboratory report LBL-22713 (Dec. 1986).
3. T. J. McCarville, W. R. Meier, C. C. Carson, J. D. Gordon, and B. B. Glasgow, "SAFIRE - A Systems Analysis Code for ICF Reactor Economics," Lawrence Livermore National Laboratory report UCRL-15872, Vol. 1 (Jan. 1987).
4. B. B. Glasgow and W. R. Meier, "SAFIRE User's Manual," Lawrence Livermore National Laboratory report UCRL-15872, Vol. 2 (Jan. 1987).

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1  CASCADE REACTOR; MARCH 1987
2  IACCT=1,
3  IFLAG=1, PEFLAG=815.0, PEERR=1 E-2,
4  RPRATE=5.0, DRP=1.0, RPFLAG=5.0,
5  TENERG=3.0, DTE=1.0, TEFLAG=10.0,
6  SHELL=1.0, ETA=0.02
7  $END
8  $CAVIT=9, NCAVIT=1
9  $END
10 $IDRIVE=5
11 $END
12 $END
13 $NUMIT=1, NYEAR=1985
14 $END
15 $IPRNT=1
16 $END
17      450.      1600.

```

Figure 1. Input file for Cascade chamber with MDAC HIB driver. (Note that with Cascade, NAMELIST LMWIN is not read.)

ENTER SAFIRE: ICF SYSTEMS ANALYSIS CODE

THE SAFIRE CODE HAS MANY AUTHORS WHO HAVE CONTRIBUTED
OVER THE YEARS. THE MOST RECENT AUTHORS INCLUDE:

WAYNE MEIER - LLNL, DAVE BERNHARD - TRW,
JIM GORDON - TRW, TOM MCCARVILLE - TRW,
CHRIS CARSON - TRW, BRUCE GLASGOW - TRW
LAST CHANGE FEB. 18, 1987

CASE TITLE: CASCADE REACTOR, MARCH 1987

FINAL TRANSPORT DETAILS:																
EIGN	NBFT	---OPTIMUM---			---ACTUAL---			BGAM	RANGE	RSPOT	FLEN	BCLETMAX	C2702	C2704	C2705	C27
		THET	EMIT	THMAX	THET	EMIT	THMAX									
9.	20	.0174	21.32	.0113	.0113	17.76	.393	.273	1.73	8.22	1749	731.	18.	25.	961.	
8.	24	.0194	27.09	.0119	.0119	21.55	.369	.229	1.97	8.22	1603.	701.	20.	30.	935.	
7.	30	.0220	35.38	.0126	.0126	26.66	.345	.184	2.28	8.22	1451.	650.	25.	39.	885.	
6.	40	.0236	47.80	.0133	.0133	33.86	.319	.144	2.69	8.3	1293.	619.	32.	54.	869.	
6.	40	.0236	47.80	.0133	.0133	33.86	.319	.144	2.69	8.3	1293.	619.	32.	54.	869.	

Figure 2. Output file for input shown in Illustration 1. In this example, SAFIRE iterates on driver energy to find a specified new electric power. The printout of final transport details is given on each iteration. Only the final iteration is shown here.

CHAMBER TYPE: CASCADE

DESCRIPTION:
 DRIVER TYPE: HEAVY ION BEAM
 GAIN CURVE: $R^{3/2}$ R = .02
 CHAMBER TYPE: CASCADE
 NUMBER OF CHAMBERS PER UNIT: 1
 NUMBER OF UNITS PER PLANT: 1
 NUMBER OF DRIVERS: 1
 NUMBER OF TARGET FACTORIES: 1

PLANT PARAMETERS:
 CHAMBER PULSE RATE (HZ): 5.00
 DRIVER ENERGY (MJ): 4.16
 TARGET GAIN: 71.2
 TARGET YIELD: 295.9
 THERMAL POWER (MWT): 1646.4
 THERMAL CYCLE EFFICIENCY (%): 54.0
 HEAT REJECTED (MWT): 757.7
 AVAILABILITY FACTOR (%): 70.0

ELECTRIC POWER BALANCE (MWE):
 GROSS ELECTRIC POWER: 888.7
 DRIVER POWER/UNIT: 54.7
 PUMPING POWER: 5.0
 OTHER BOP POWER: 10.0
 NET ELECTRIC POWER: 819.0

ECONOMIC FACTORS (%):
 ESCALATION RATE: 6.00
 GENERAL INFLATION RATE: 6.00
 AFTER-TAX COST OF MONEY: 7.00
 REAL COST OF MONEY: 2.83
 CURRENT DOLLAR FIXED CHARGE RATE: 16.22
 CONSTANT DOLLAR FIXED CHARGE RATE: 8.32

INDIRECT AND TIME-RELATED COST FACTORS:
 CONSTRUCTION SERVICES (F91): 0.200
 HOME OFFICE ENG. & SERVICES (F92): 0.150
 FIELD OFFICE ENG. & SERVICES (F93): 0.100
 OWNERS COST (F94): 0.070
 PROJECT CONTINGENCY (F95): 0.100
 CONSTRUCTION TIME (YR): 8.000
 ESCALATION DURING CONST. (FEDC): 3.323
 INTEREST DURING CONST. (FIDC): 0.420

Figure 2. (Continued)

HEAVY ION BEAM DRIVER INFORMATION
BASED ON MCDONNELL DOUGLAS MODEL

FINAL TRANSPORT SUMMARY FOR DOUBLE-SIDED IRRADIATION:	
POLE TIP FIELD (T)	1.0000
ION ENERGY (GEV)	6.0000
ION MASS (AMU)	130.0000
ION CHARGE STATE	3.0000
GAIN PARAMETER (R*R**1.5)	0.0200
ION RANGE IN TARGET (G/CM**2)	0.1436
TARGET AVERAGE Z	13.0000
BEAM STIFFNESS (T-M)	42.9033
FINAL TRANSPORT BEND RADIUS (M)	21.4516
FINAL FOCUS CONVERGENCE ANGLE (RAD)	0.013344
CHAMBER RADIUS + STANDOFF (M)	7.0000
FINAL MAGNET LENGTH (M)	0.6816
FINAL MAGNET RADIUS (M)	0.5259
FINAL FOCUS SYSTEM LENGTH (M)	66.1991
FINAL SPOT SIZE (MM)	2.6870
BEAM POWER DENSITY (TW/CM**2)	1299.7963
FINAL PULSE LENGTH (NSEC)	14.0976
UNNORMALIZED EMITTANCE (UR-M)	33.86
BEAMLET PERVEANCE	0.000169
FINAL TRANSPORT SYSTEM LENGTH (M)	154.1109
DELAY LINE LENGTH (M)	0.0000
SWITCH YARD LENGTH (M)	0.0000
CURRENT PER BEAMLET (A)	1228.4154
NUMBER BEAMLETS IN FINAL TRANSPORT	40
ACCELERATOR SUMMARY:	
NORMALIZED ACCELERATOR COST (M\$)	658.62
ACCELERATOR REPETITION RATE	5.0000
ACCELERATOR EFFICIENCY (%)	37.9648
NUMBER OF BEAMS IN ACCELERATOR	16
ACCELERATOR LENGTH (KM)	1.2636
ACCELERATOR OPERATING SCENARIO	SINGLE-PULSED
DRIVER COST SUMMARY:	
C27 DRIVER TOTAL DIRECT COST (M\$)	869.33
C2701 ION SOURCE/PREACCELERATOR (M\$)	123.73
C2702 ACCEL MODULES AND PWR SUP (M\$)	618.64
C2703 PULSE COMPRESSION SYSTEM (M\$)	0.00
C2704 BEAM TRANSPORT SYSTEM (M\$)	31.84
C2705 FINAL FOCUS SYSTEM (M\$)	53.52
C2706 COOLING SYSTEM (M\$)	7.40
C2707 ACCEL AND TRANS VACUUM (M\$)	3.70
C2708 DRIVER MAINTENANCE EQUIP (M\$)	5.50
C2709 I&C (M\$)	25.00

Figure 2. (Continued)

ICF ECONOMIC EVALUATION FOR 1 UNIT POWER PLANT			
ACCOUNT	ACCOUNT TITLE	M\$	
20	LAND AND LAND RIGHTS	5.0	
21	STRUCTURES AND IMPROVEMENTS	84.1	
22	REACTOR PLANT EQUIPMENT	281.4	
23	TURBINE PLANT EQUIPMENT	181.5	
24	ELECTRIC PLANT EQUIPMENT	70.1	
25	MISCELLANEOUS PLANT EQUIPMENT	16.3	
26	MAIN HEAT REJECTION EQUIPMENT	21.2	
27	DRIVER EQUIPMENT	869.3	
28	TARGET FACTORY EQUIPMENT	85.7	
	TOTAL DIRECT COST	1614.5	
91	CONSTRUCTION SERVICES	322.9	
92	HOME OFFICE ENGINEERING AND SERVICES	242.2	
93	FIELD OFFICE ENGINEERING AND SERVICES	161.5	
94	OWNER'S COST	113.6	
95	PROJECT CONTINGENCY	245.4	
	TOTAL OVERNIGHT COST	2699.5	
		CURRENT\$	CONSTANT\$
96	ESCALATION DURING CONSTRUCTION	871.2	0.0
97	INTEREST DURING CONSTRUCTION	1133.9	252.2
	TOTAL CAPITAL COST	4704.6	2951.7
	COST OF ELECTRICITY		
	CAPITAL	15.20	4.89
	FUEL	0.02	0.01
	O&M	5.01	1.61
	TOTAL	20.23	6.51

CONSTANT \$ RESULTS IN 1985 DOLLARS
CURRENT \$ RESULTS IN 1993 DOLLARS

Figure 2. (Continued)