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MODELING A HEAVY ION DRIVER FOR AN ICF POWER PLANT

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Summary

This paper presents the point reference design of a heavy ion driver which results from a parametric scaling model of a commercial ICF power plant. The power plant consists of the driver, the reactor, the pellet factory, and the balance of plant which generates and distributes the electric power to sell as well as the power to run the driver. The results presented in this paper deal with the driver and its interface to the reactor. These results are obtained with a heavy ion driver model which is part of a larger model developed by the Westinghouse Electric Corporation for the entire power stations.

The theoretical model which has been developed for the heavy ion driver attempts to set forth a self consistent set of equations that define an envelope within which real drivers must fall. Many technically critical parts of a driver have been intentionally left out where it was felt that they did not impact the basic conceptual design, system size, or cost. Detailed discussions of all of the subsystems can be found in the proceedings of the Heavy Ion Fusion Workshops[1-4] and the IEEE Biannual Accelerator Conferences.[5-7]

The scaling of costs is based on the base costs for Fermilab and the AGS at BNL given in the Proceedings of the Heavy Ion Fusion Workshop[2] of October 17-21, 1977, pages 141-145. The power supply costs are based on a recent quote by Continental to ANL for a 5 MW unit delivered, but not installed, of $.20/watt peak.

Introduction

The function of the driver is to deliver a properly shaped pulse of energetic heavy ions to the pellet. For a heavy ion driver this implies ions of atomic mass from Xe 131 to U 238 at kinetic energies from 5 GeV to 20 GeV.

These ions are to be focused on a target spot ranging from 1 mm to 5 mm in radius. The pulses are to be 6 n sec - 20 n sec long containing 1 MJ to 10 MJ of energy per pulse.

TABLE 1

PARAMETERS REQUIRED FOR HEAVY ION DRIVER

Ion:	Xe^+ or Xe^{++}
Ion Energy:	10 GeV
Target:	2.5 mm Radius
Beam Energy:	2 MJ
Beam Power:	150 TW
Pulse Length:	13 nsec

Because the charge state has an extreme influence on size and cost, two almost identical systems meeting the design requirements are described in Tables 2 through 7. The systems are based on either Xe^+ or Xe^{++} (single and doubly ionized xenon). For these reference designs the ion energy is 10 GeV, the beam energy is 2 MJ, the beam power is 150 TW, the pulse length is 13 nsec, and the pellet radius 2 mm. When only one value of a parameter is listed it is the same for both systems. Figure 1 is a schematic representation of a heavy ion driver base on Xe^+. In general, all parts of the Xe^{++} system are half the size of the corresponding part of the Xe^+ system. However, the number of storage rings required by the Xe^{++} system is four times greater than that required by the Xe^+ system. The low β, Wideroe, accelerator ends at "a" on the figure ; the high β, Alvarez, accelerator starts at "a" and continues to "b" on the figure.

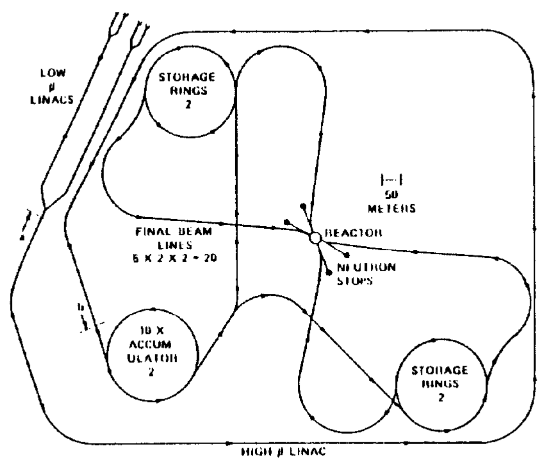

Figure 1 Schematic Representation of Heavy Ion RF Linac Driver 10 GeV Xe^+

Tables 2-8 will describe the seven blocks comprising the driver and reactor interface by listing important parameters and their values.

TABLE 2

PARAMETERS DESCRIBING THE ION SOURCE AND PREACCELERATOR

Ion	Xenon	
Normalized Emittance	$\varepsilon_s = 3.2 \times 10^{-7}$ m-rad	
Current per source	$i_s = 25$ mA	
Charge state of ion	$Z = 1$	
Atomic mass of ion	$A = 131$	
Kinetic Energy of Preaccelerator	$T_0 = 2 \times 10^{-3}$ GeV	
Number of Sources	$Xe^{++}, n_s = 4$	$Xe^+, n_s = 8$

Bending and Final Focusing Elements

The heavy ion driver is defined as ending with the beam transport line; the final bending and focusing elements are considered part of the reactor block because of the strong influence of the neutron flux on their design. The essential elements of the interface are: bending magnet (to bend the ion beam away from the neutron path), neutron dump (to capture the backstreaming neutrons) and final focusing triplet. These are shown in Figure 2. A greatly expanded vertical view of the action of the final focusing triplet is shown in Figure 3. The final focusing

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TABLE 3

PARAMETERS DESCRIBING THE LOW β ACCELERATOR WIDEROE CAVITIES

Total energy 0.16 MJ

	Xe^{++}		Xe^{+}
Total power to beam	37.9 MW		75.8 MW
to cavities	58.3 MW		116.6 MW
First Section			
Operating Frequency		12.5 MHz	
2 MeV in/20 MeV out; 1:1 Beam Loading			
Magnetic Field, B		> 1 Tesla	
Number of Sections	4		8
Length of each Section		18 m	
Second Section			
Operating Frequency		50 MHz	
20 MeV in/100 MeV out; 1:1 Beam Loading			
Magnetic Field, B		∼ 0.65 Tesla	
Number of Sections	2		4
Length of each Section		80 m	
Third Section			
Operating Frequency		100 MHz	
100 MeV in/600 MeV out; 2:1 Beam Loading			
Magnetic Field, B	1.67T		0.056T
Number of Sections	1		2
Length of each Section	350 m		700 m

TABLE 4

PARAMETERS DESCRIBING THE HIGH β LINAC ALVAREZ CAVITIES

Total energy 1.84 MJ

	Xe^{++}		Xe^{+}
Total power to beam	460 MW		920 MW
to cavities	614 MW		1227 MW
Operating Frequency		200 MHz	
0.6 GeV in/10 GeV out; 3:1 Beam Loading			
Magnetic Field, B		∼ 0.002 Tesla	
Length of Linac	2760 m		5520 m

TABLE 5

PARAMETERS DESCRIBING THE DEBUNCHER, MULTIPLIER RINGS AND COMPRESSOR

	Xe^{++}		Xe^{+}
Debuncher			
Operating Frequency		200 MHz	
Power	2 MW		4 MW
Length of debuncher	50 m		100 m
Multiplier Rings			
2 Rings			
10 revolutions to fill			
Average dipole field		1.8 Tesla	
Radius of Ring	45 m		90 m
Compressor			
ΔT introduced to produce compression		2% T = 0.2 GeV	
Length of compressor	55 m		110 m

triplet causes the ion beam which is expanding after leaving the first focusing magnet to converge towards the focal spot some 15 meters away from the edge of the magnet. The 20 transport lines for the Xe^{+} system terminate in ten final focusing lens on each side of the reactor. Figure 4 shows a possible arrangement of the final focusing magnetics. These triplets weigh of the order of 90 tones each. The final focusing system is summarized in Table 8.

TABLE 6

PARAMETERS DESCRIBING THE STORAGE RINGS

	Xe^{++}		Xe^{+}
Storage time	4 msec		2 msec
Number of rings	16		4
Radius of rings	45 m		90 m
Average dipole field		1.8 Tesla	
Vacuum in Ring	1.3×10^{-9} Torr		2.7×10^{-9} Torr
Fill factor		50%	
Stacking in ring		(10 x 10)	
ϵ_{SR} Normalized Emittance		2.6×10^{-5} m-rad	
Number of bunches per ring	1		5
Compression in ring		7X	
Revolutions to compress	8		4
Time per revolution	2.94 μsec		5.89 μsec
Current at extraction	70 A		70 A

TABLE 7

PARAMETERS DESCRIBING THE FINAL TRANSPORT SYSTEM

	Xe^{++}	Xe^{+}
Number of lines	16	20
Compression from storage ring to target	26.8	10.7
Paraxial distance from storage ring to pellet	1334 m	500 m
Initial current per line	70 A	70 A
Final Current at pellet	1875 A	750 A
Current at end of transport	752 A	306 A
First quad pole tip field	0.026 Tesla	0.018 Tesl
Last quad pole tip field	0.92 Tesla	0.17 Tesla
Geometric mean B	0.025 T	0.016 T

TABLE 8

PARAMETERS DESCRIBING THE FINAL FOCUS AND REACTOR

	Xe^{++}		Xe^{+}
Reactor inner radius		10 m	
Distance from pellet to front of final focusing magnet	13.9 m		15 m
B_{max} of final element	4.1 T		4.8 T
Total length of focusing triplet	6 m		8 m
Distance from pellet to first focusing magnet	48 m		78 m

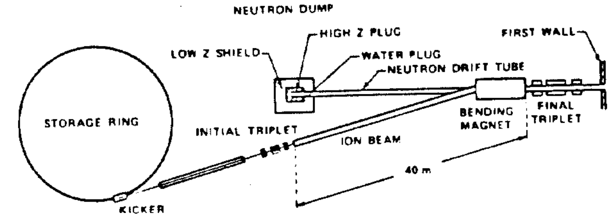

Figure 2 Interfacing Between Storage Ring, Focusing Triplet, Bending Magnet and Reactor Chamber

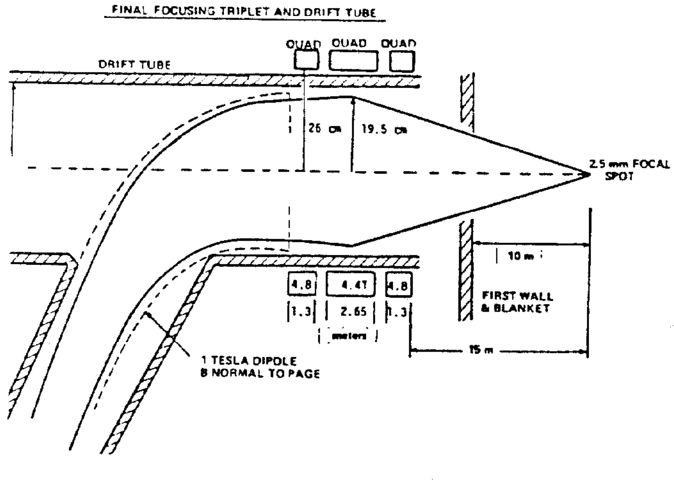

Figure 3 Detail of Heavy Ion Beam Focusing

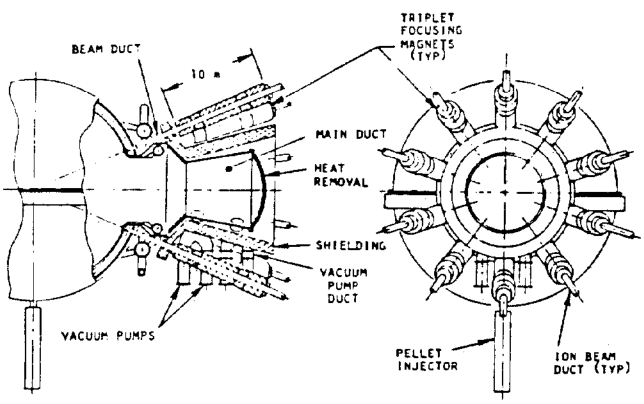

Figure 4 Reaction Chamber Interfaces Showing Relationship Between Focusing Magnets, Ion Beam Ducts and Vacuum Pumps

System Operations and Cost

The accelerator portion of the driver stores 2 MJ of energy in the storage rings in the form of energetic ions 10 times per second. Each storage ring has one kicker magnet to extract each bunch from the ring. The total time for the beam to compress is 28μsec for Xe^{+} and 35μsec for Xe^{++}. The beams must be in phase with each other to less than 1 nsec, but the absolute timing is not critical since the pellet travels a negligible distance in one cycle period of a storage ring. The synchronization of the beams requires a phase accuracy within the ring of $1:10^4$ which is well within the state of the art. The final magnet systems focus the ions onto the pellet and bend the beam into the line of sight of the pellet allowing the neutrons to stream into the neutron dumps. Because the components of the heavy ion driver and interface systems are based on a mature technology, it is possible to assign estimated costs to the blocks described in the preceding parts of this section. These costs are listed in Table 9.

TABLE 9

ESTIMATED COSTS FOR MAJOR CONSTITUENTS OF A 2 MJ, 10 GeV HEAVY ION DRIVER-REACTOR INTERFACE SYSTEM

	Xe^{++}	Xe^{+}
Ion source and pre-accelerator	\$ 7 M	\$ 14 M
Low β, Wideroe, accelerator	105	210
High β, Alvarez, accelerator	484	968
Debuncher, multiplier rings, etc.	29	58
Storage rings	194	97
Final transport	586	176
Total Driver Cost	\$1405 M	\$1523 M

These figures show that the anticipated cost benefit from going to higher charge state ions is not very great. The cost of the first four blocks for Xe^{++} is indeed half that for Xe^{+}; however, the last two blocks for the Xe^{++} are twice to four times as expensive as Xe^{+}. In either event, the total cost shown in Table 9 is quite high and should be the object of cost reduction studies.

Acknowledgment

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