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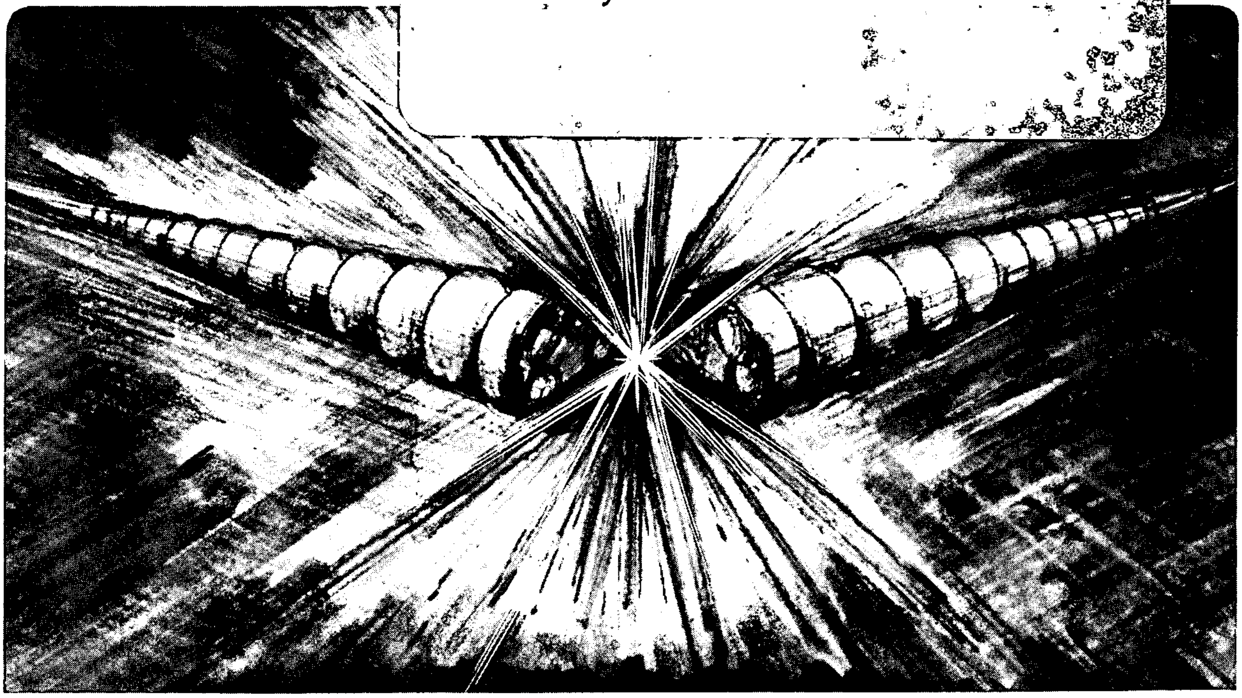

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THE COST OF INDUCTION LINAC DRIVER FOR INERTIAL FUSION FOR VARIOUS TARGET YIELDS*

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THE COST OF INDUCTION LINAC DRIVERS FOR INERTIAL FUSION FOR VARIOUS TARGET YIELDS*

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ABSTRACT

The cost of induction linac accelerators for inertial fusion using mass 200 ions at a charge state of +3 for target yields of 300, 600, and 1200 MJ is presented. The ions are injected into the accelerator at 3 MV, and accelerated to the required voltage appropriate to the desired target yield. A cost comparison of the low voltage portion of the accelerator (3-50 MV) is made between a system with 64 and one with 16 superconducting quadrupoles. The design of the low voltage portion which yields the minimum-cost accelerator designs for several target yields and a fusion power of 3000 MW is presented.

INTRODUCTION

An induction linear accelerator that produces an energetic (5 to 20 GeV) beam of heavy (130 to 238 amu) ions is a prime candidate as a driver for inertial fusion. The required accelerator output parameters for an ion species can be determined from the target requirements for a given fusion energy yield, and the cost and efficiency of various accelerator configurations to produce the required output can be determined. In this study we use mass 200 ions.

DETERMINATION OF THE ACCELERATOR OUTPUT PARAMETERS

The required accelerator output parameters for a given target yield can be determined for a single shell target design using the Lindl-Mark gain curves.[1] These include the total energy and, for a given ion species, the emittance and ion kinetic energy. For a given target yield, the output energy, W, is determined based on the upper bound of the Lindl-Mark "best estimate" gain curve. Also determined is the $r^{3/2}R$ parameter where R is the range of the ions in g/cm^2 in the target material and r is the target spot radius which must satisfy

$$0.1\ W^{1/3} < r < 0.2\ W^{1/3}\ (W, MJ; r, cm)\ . \qquad (1)$$

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From the $r^{3/2}R$ parameter and the target spot radius, the desired range can be determined. From this range, the required ion kinetic energy can be specified. From the ion kinetic energy and spot radius, for a given angle of convergence, the maximum normalized emittance of the accelerator beamlets can be determined assuming that it dominates the spot radius. This completes the description of the required accelerator output. Associated with the target gain and beam energy is a peak power requirement which can be independently modulated by the final transport drift lines.

EARLY COST AND PERFORMANCE RESULTS

The cost and performance of the accelerator were determined using the modified cost optimization LIACEP[2] code. We investigated single shell target yields of 300, 600, and 1200 MJ and fusion powers between 1500 and 6000 MW for the singly-charged mass 200 ions. Accelerator configurations accommodating 4, 8, and 16 simultaneous beamlets were studied, with undepressed and depressed tunes (refer to "D. Keefe, these proceedings" for definition) of the the transport lattice of $\sigma_0 = 75°$ and $\sigma = 24°$, respectively. The results are given in Table I for an angle of convergence in the chamber of 0.015 radians and a spot radius due only to emittance. The efficiency and costs (in 1979 dollars) of the accelerators for a fusion power of 3000 MW and an initial voltage of 50 MV are also given for accelerator configurations of 4, 8, and 16 beamlets. The efficiencies are greater than 20%, resulting in a ratio of fusion power to accelerator input power greater than 28. The minimum cost designs are near the maximum efficiency designs.

Table I. Accelerator Ouput Characteristics, Efficiencies and 1979$ Costs for 300, 600, and 1200 MJ Target Yields and 3000 MW Fusion Power using 200 amu, q = +1 Ions.
$\phi = 0.5$ MV/m; $\sigma_0 = 75°$, $\sigma = 24°$
Initial Voltage = 50 MV; Spot Radius = 0.1 $W^{1/3}$ cm
Range = R g/cm^2

Yield, MJ		300	600	1200
Pulse Rep. Rate, hertz		10	5	2.5
Energy, (W) MJ		2.91	4.25	6.57
Gain (G)		103	141	183
$r^{3/2}R$, 10^3 cm$^{-1/2}$g		7.2	10.4	15.9
Normalized Emittance (ϵ_n), μm-r		7.15	8.65	10.8
Ion Kinetic Energy, (E_i), GeV		10.12	11.46	13.24
Cost, G$				
Beamlets:	4	1.149	1.275	1.483
	8	1.107	1.227	1.427
	16	1.152	1.276	1.473
Efficiency, (η)%				
Beamlets:	4	21.2	21.5	21.6
	8	22.7	24.6	26.2
	16	20.7	23.0	25.3

COST REDUCTION STRATEGY

The costs can be reduced by increasing the charge state, increasing the undepressed tune, and decreasing the depressed tune limits. For example, the cost of the 4.25 MJ, 8 beamlet accelerator above 50 MV that produces 11.46 GeV ions can be reduced from 1.227 G$ to 0.6393 G$ (1979$) by increasing the ion charge state to +3, increasing the undepressed tune to 85°, and decreasing the depressed tune to 10.5° while increasing the number of beamlets to 16. From perveance considerations, this accelerator system will require at least 16 beams focussed on target. The cost can be decreased further to 0.5136 G$ by increasing the allowable vacuum surface flashover voltage gradient (ϕ) from 0.5 MV/m used in the Austin Study[2] to 1.0 MV/m used in the Palaiseau Study[3]. The effect of these cost reduction techniques is to reduce the length of the accelerator above 50 MV from 10.7 to 2.23 km, and increase the efficiency from 24.6 to 34.5%. The somewhat longer front end (<50 MV) of the higher charge state option is more than offset by this large length reduction.

The cost of this accelerator can be further reduced from 0.5136 to 0.4826 G$ by double pulsing a 2.125 MJ accelerator. However, the efficiency decreases from 34.5% to 20.8% using current technology. Complete reactor plant system studies[4,5] have shown that the increased balance of plant costs due to the lower efficiency of double pulsing offsets the capital cost advantage of double pulsing[6].

The increase in the charge state (q) of the ions may be made possible by the development of the metal vapor vacuum arc (MEVVA) source which produces large quantities of ions in a range of charge states for most metals.[7] The higher charge state savings are due to the shortening of the accelerator, with savings in the quantity of cores and quadrupoles. Some of the cost savings may be used up by the increased number of beamlets which scales as q^2 in the final focus to meet perveance constraints. These are discussed by Lee.[8] For the case selected for this paper, the number of beamlets from perveance considerations in the final focus does not exceed the number of beamlets in the accelerator.

The increase of the undepressed tune to 85° is speculative. However, there is some experimental evidence that this value of undepressed tune may be achieved.[8]

The use of a vacuum surface flashover voltage gradient of 1 MV/m results in the high acceleration gradients of about 2 MV/m in the final regions of the driver. These high acceleration gradients are adventurous, and caused by the model used to estimate the enhancement of the flashover gradient at short pulse durations.

The use of double pulsing to reduce the cost of the accelerator is most effective for ions with low kinetic energy. Cost savings of 30% can be realized with low kinetic energy ($\simeq$5 GeV) ions.[9] A possible strategy for a low cost accelerator using low kinetic energy ions may be to use double pulsing coupled with a charge state of +2. This may ease the perveance conditions in the final focus and reduce the number of beamlets in the final focus elements to the target. Advances in tube technology may reduce the power consumption of the pulsers, which will increase the efficiency of the double pulsed accelerator.

ACCELERATOR COST AND PERFORMANCE

Three accelerators were analyzed using LIACEP to give target yields of 300, 600, and 1200 MJ using the minimum spot radius and the upper bound of the best estimate gain curve. The fusion power, which is the product of fusion yield and pulse repetition frequency, was fixed at 3000 MW. The charge state +3, 200 amu ions are injected into the accelerator with a kinetic energy of 9 MeV. This low voltage section of the accelerator consists of 64 beamlets, using superconducting quadrupoles and amorphous iron cores. The transition ion kinetic energy for which it becomes cost effective to combine the 64 beamlets into 16 beamlets is the energy at which the total unit costs for the 64 beamlet system is equal to that of the 16 beamlet system. This transition ion energy is typically between 400 and 600 MeV for the cases considered in this paper. The 64 beamlets are then combined into 16 beamlets, and accelerated to the desired final kinetic energy. The accelerator output characteristics are as shown in Table I, and repeated in Table II.

The undepressed tune σ_0 of 85° and the allowable vacuum surface flashover voltage gradient 1 MV/m are used for these accelerators. The depressed tune for each of the accelerators is given in Table II.

The costs and performance of the accelerators to produce target yields of 300, 600, and 1200 MJ are given in Table II for a fusion power of 3000 MW. The cost of the accelerator increases with the target yield, but the performance, measured as ηG (accelerator efficiency times target gain), also increases, resulting in a lower recirculating power fraction to the accelerator. The costs of the low voltage (<50 MV) section are about 20% of the accelerator costs.

Table II. Accelerator Output Characteristics, Efficiencies and 1979$ Costs for 300, 600, and 1200 MJ Target Yields and 3000 MW Fusion Power using 200 amu, q = +3 Ions.
$\phi = 1.0$ MV/m; $\sigma_0 = 85°$
Initial Voltage = 3 MV; Spot Radius = $0.1 \times W^{1/3}$ cm
Range = R g-cm/cc; N = 16 beamlets, $V > V_c$

Yield, MJ	300	600	1200
Energy, (W) MJ	2.91	4.25	6.57
Gain (G)	103	141	183
$r^{3/2}R$, 10^3 cm$^{-1/2}$g	7.2	10.4	15.9
Emittance (ϵ_n), μm-r	7.15	8.65	10.8
Ion Kinetic Energy, (E_i), GeV	10.12	11.46	13.24
Pulse Repetition Frequency, hertz	10	5	2.5
64 Beamlet Cost to 50 MV, M$	108	124	162
64 to 16 beamlet transition voltage (V_c), MV	133	160	180
ϵ_n/σ, μm-r/degree, $V<V_c$	1.1	0.82	1.1
Depressed Tune (σ), $V<V_c$, degrees	7.5	10.5	10
Total Cost, M$	551.5	633.1	748.7
Total Length, km	1.97	2.22	2.57
Total Efficiency (η)%	26.9	28.7	29.0
ηG	27.7	40.6	52.9

The unit costs (1979$) per volt for a driver which will produce a target yield of 300 MJ are shown in Fig. 1 as a function of the ion energy. At low ion energies, the core costs dominate the total cost. At high ion energies, the structure (including insulators) and pulsers are the more costly units. Integrating the costs over the ion kinetic energy gives the total costs for the complete accelerator. The core costs are about 33% of the total cost of the accelerator. The superconducting magnet costs represent about 23% of the total costs of the accelerator. The structure (including insulators) and the pulsers represent about 17 and 15%, respectively, of the total costs. These cost percentages will change when the costs are in 1985$, as discussed later in this paper.

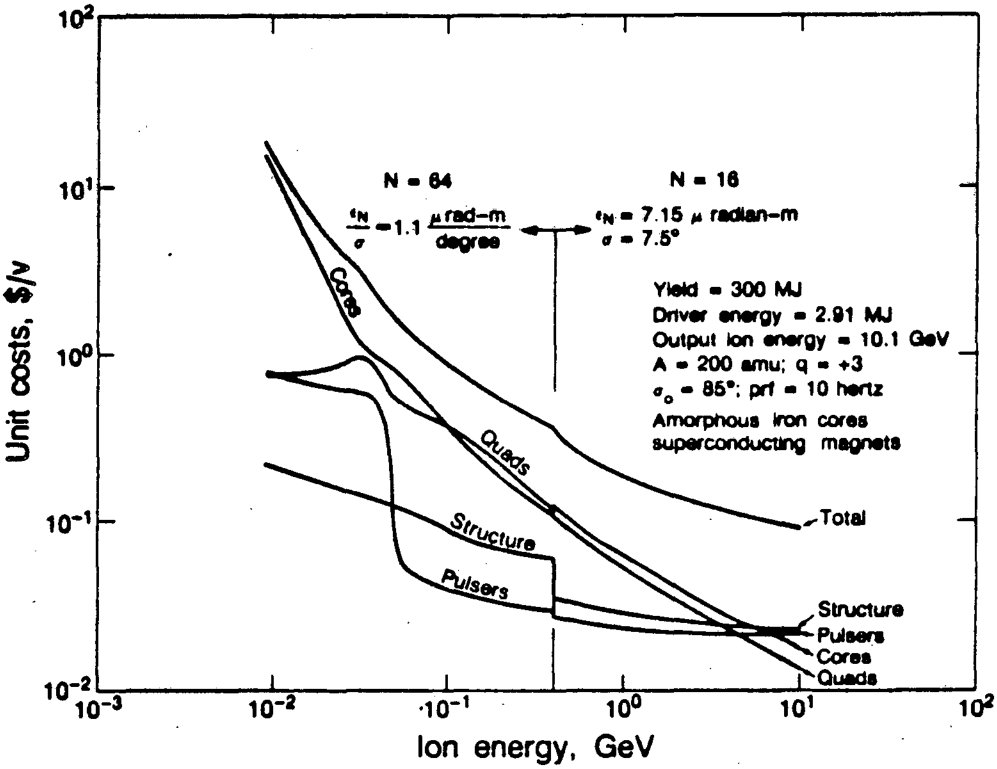

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Fig. 1. Distribution of the accelerator costs (1979 dollars per volt) as a function of ion kinetic energy for a 300 MJ target yield producing a fusion power of 3000 MW. The transition ion energy for 64 beamlets to 16 beamlets is 400 MeV (133 MV). The depressed tune is 6.5° below and 7.5° above the transition ion energy.

The results for the low voltage section (<50 MV), as computed by LIACEP and shown in Fig. 1, are not very satisfactory. The cost differential between the 64 beamlet system and the 16 beamlet system is actually larger than currently calculated by LIACEP. This is due in part to not having a maximum velocity tilt ($\delta\beta/\beta$) limit in the code.[10] This limit on the tilt will increase the costs of the low voltage region of the accelerator where the beam length is long by forcing a lower acceleration rate and increasing the cost of the quadrupoles. The effect of the tilt limit will be more severe with the smaller number of beamlets than with the larger number of beamlets. The costs of the pulsers shown in Fig. 1 can be reduced by driving several modules with a single pulser in the region where the ion kinetic energy is less than 60 MeV. This could reduce the pulser cost per volt by perhaps an order of magnitude in the low voltage (<20 MV) region. The LIACEP results show very low superconducting quadrupole fields in the low voltage section of the accelerator due to the constraint that their length to bore ratio must be greater than a minimum specified number. This constraint results in large beamlet diameters, with concurrent large quad and core costs. By relaxing this constraint, the depressed tune could be increased which will increase the quadrupole field and reduce the beamlet diameter, resulting in a reduction in the quad and core costs.[10,11] Also, the use of electrostatic quadrupoles in the low voltage region may decrease the costs. LIACEP does not yet contain a good electrostatic focus system subroutine.

The combining of 64 beamlets into 16 beamlets in space and time may result in a cost savings. This combination of beamlets will result in an increased emittance in the region with the smaller number of beamlets (or conversely, require a reduced emittance in the region with the larger number of beamlets). Thus, there is a maximum number of beamlet combinations that can be allowed that will give the required spot size on target with a given source brightness. In addition, the depressed tune should be held proportional to the emittance. The output emittance is determined from target considerations, and the depressed tune in the high voltage portion of the accelerator is selected to minimize the cost of this portion of the accelerator. The decrease in emittance in the low voltage section due to the combining of beamlets will require a reduction in the depressed tune to minimize the cost in this section. There may be a lower limit to the depressed tune before instabilities occur that may offset some of the cost advantages of combining beamlets.

Additional cost savings can be made by changing the depressed tune along the length of the accelerator.[12] For the case of the 4.25 MJ driver given in Table II with a vacuum surface flashover voltage gradient of 0.5 MV/m, 16 beamlets and an initial ion energy of 150 MeV, the cost savings, by reducing the depressed tune from 10.5 to 8° for ion energies between 200 and 1500 MeV, was greater than 7 M$.

COST ESCALATION

The costs of the accelerators are given for a mature technology in 1979 dollars. The results of the application of cost escalation factors for the various accelerator components from 1979$ to the 1985$ for the three accelerators described in Table II are given in Table III. The pulsers become the most expensive unit in the accelerator, narrowly exceeding the core costs. Placing the new cost factors into LIACEP may result in different accelerator designs to achieve a minimum cost configuration.

Table III. Accelerator Cost Estimates Escalated from 1979 Dollars to 1985 Dollars.
$P = 3000$ MW$_f$; $A = 200$ amu; $q = +3$
$\phi = 1.0$ MV/m; $\sigma_0 = 85°$; $V_0 = 3$ MV

Target Yield, MJ	300	600	1200
Accelerator Energy, MJ	2.91	4.24	6.57
1979 Costs, M$	550	630	750
1985 Costs, M$	710	790	910
Escalation, %	30	24	22
$/J (1985$)	250	190	140

CONCLUSIONS

Induction linac drivers with output energies of 2.91, 4.25, and 6.57 MJ are necessary to obtain yields of 300, 600, and 1200 MJ, respectively, from single shell targets. The accelerators, using 200 amu, charge state +3 ions injected with a kinetic energy of 9 MeV, feature superconducting quadrupoles for beam transport and amorphous iron cores for acceleration.

The costs of these drivers producing 3000 MW of fusion power roughly scaled from 1979 dollars to 1985 dollars decrease from 250 to 140 $/J of driver energy with an increase in target yield from 300 to 1200 MJ. The ratio of fusion power to power into the driver increases from 27.7 to 52.9 with the increase in target yield. These drivers are less than half the cost of the more conservative, charge state +1 drivers.

Further modifications must be made to the cost minimization code LIACEP to better assess the low voltage section of the driver. These modifications include placing a limit on the velocity tilt and reexamining the other constraints that prevent the use of the superconducting quadrupoles at their maximum fields. Finally, the cost algorithms should be modified to reflect the 1985 costs of material and labor.

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