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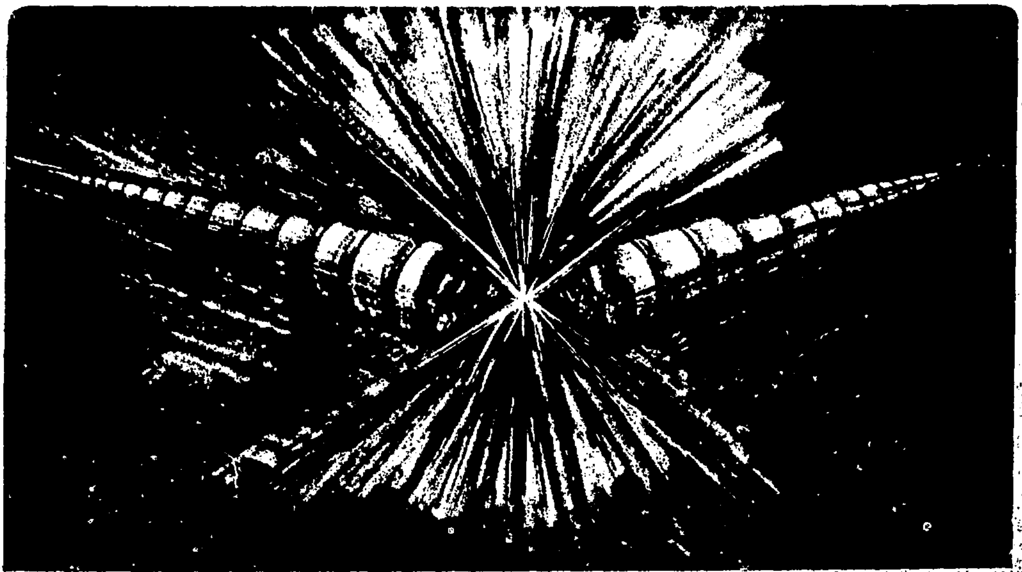

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ABSTRACT

Optimized cost estimates for induction linac accelerators using mass 133 ions at a charge state of +2 producing inertial fusion target yields of 300, 600, and 1200 MJ are 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 these drivers is made with drivers using mass 200, charge state +3 ions for several target yields and a fusion power of 3000 MW.

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 133 ions, and compare the results with those for mass 200 ions

DETERMINATION OF THE ACCELERATOR OUTPUT PARAMETERS

The required accelerator output parameters for a given target yield can be determined for a given target design using the Lindl-Mark gain curves.[1] These include the total energy and, for a given ion mass, 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

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

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 in the final focus, the maximum normalized emittance of the accelerator beamlets can be determined assuming that it dominates the convergence. This completes the description of the required accelerator output. Associated with the target gain and beam energy is a peak power requirement which is independently modulated by varying the lengths of the final transport drift lines.

ACCELERATOR COST AND PERFORMANCE

Three accelerators were analyzed using LIACEP, the modified optimization code cost with 1979$ 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.[2] The fusion power, which is the product of fusion yield and pulse repetition frequency, was fixed at 3000 MW. The charge state +2, 133 amu ions are injected into the accelerator with a kinetic energy of 6 MeV. The subsequent 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 the 16 beamlet system. This transition ion energy (qV_c) is typically between 200 and 400 MeV for the 133 amu, charge state +2 cases considered. 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.

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

The costs and performance of the accelerators are given in Table I. The cost of the accelerator

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Table I. Accelerator Output Characteristics, Efficiencies and 1979 and 1985$ Costs for 300, 600, and 1200 MJ Target Yields and 3000 MW Fusion Power using 133 amu, q = +2 Ions.
● = 1.0 MV/m; $\sigma_0 = 85°$
Initial Voltage = 3 MV; Spot Radius = $0.1 \times W^{1/3}$ cm
Range = R g/cm^2; 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
Normalized Emittance (ϵ_n), μm-rad	6.79	8.21	10.2
Ion Kinetic Energy, (E_i), GeV	6.077	6.885	7.953
Pulse Repetition Frequency, hertz	10	5	2.5
64 to 16 beamlet transition voltage (V_c), MV	110	150	200
ϵ_n/σ, μm-rad/degree, $V<V_c$	1.1	0.82	1.1
Depressed Tune (σ), $V>V_c$, degrees	7.1	10.1	9.5
Total Cost, M$ (1979)	545	635	757
Total Cost, M$ (1985)	706	775	913
Total Length, km	1.77	2.16	2.40
Total Efficiency (η)%	27.6	31.6	29.8
ηG	28.7	44.6	54.5

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 distribution of the accelerator costs is given in Table II in both 1979$ and 1985$ for a driver that will produce a target yield of 300 MJ and a fusion power of 3000 MW. For the driver optimized to 1979$, the cores are the most expensive component followed by the superconducting quadrupoles. Escalating this design to 1985$ results in the pulsers becoming the most expensive component followed by the core. If the driver is optimized to 1985$, the cost distribution and costs will differ from that shown in Table II.

Table II. Distribution of Accelerator Costs for a Driver Producing a Target Yield of 300 MJ and a Fusion Power of 3000 MW using 133 amu, q = +2 Ions.

Basis Year	1979	1985
Total Cost, M$	545	706
Core, %	34.2	26.5
Structure, %	15.2	5.9
Pulsers, %	14.9	34.4
Quads, %	23.6	18.3
Remainder, %	12.1	14.9

From an earlier paper, the costs of accelerators using 200 amu, charge state +3 ions to produce target yields of 300, 600 and 1200 MJ at a fusion power of 3000 MW were determined.[3] These costs are shown in Table III.

The costs of the accelerators using 133 amu, charge state +2 ions are within 2% of those using 200 amu, charge state +3 ions for a given target yield. For all cases, the charge state to mass ratio was held constant. For a given target yield, the depressed tune to normalized emittance ratios was held constant. The difference in the cost and performance for a given target yield is due to the difference in the required ion kinetic energy (and hence, particle current) of the two particle masses to satisfy the range requirement for the specified target yield.

The 1985$ cost of the accelerator using 133 amu, charge state +2 ions optimized to 1979$ costs is cheaper than that using 200 amu, charge state +3 ions for low target yields. However the final transport costs of the lower mass, lower charge state ions may be greater than the higher mass, higher charge state ions due to the increased number of beamlets on target required by the perveance in the final focus.[4] The required number of beamlets on target is about 33% greater for the 133 amu, +2 ions than for the 200 amu, +3 ions due to the difference in the required ion kinetic energy of the two particle masses to satisfy the range requirement for the specified target yield. The number of final transport of beamlets the 200 amu, +3 ions on target is matched to the 16 beamlets in the high voltage end of the accelerator such that no beam splitting is required for the final transport to the target. The 16 beamlets of the 133 amu, +2 ions from the high voltage end of the accelerator may need to be split into a minimum of 22 beamlets, with a decrease in the beamlet emittance in the accelerator to preserve the spot radius on target. The decrease in the emittance may require a lower depressed tune in the accelerator to mitigate the impact of the lower emittance on the accelerator costs. If the depressed tune is reduced too far, problems may occur in beamlet transport.[5] An additional consideration is that the emittance increases due to excessive combining and/or

Table III. Accelerator Output Characteristics, Efficiencies and 1979 and 1985$ Costs for 300, 600, and 1200 MJ Target Yields and 3000 MW Fusion Power using 200 amu, q = +3 Ions.
$\mathcal{E}$ = 1.0 MV/m; σ_0 = 85°
Initial Voltage = 3 MV; Spot Radius = 0.1 X $W^{1/3}$ cm
Range = R g/cm^2; 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	7.15	8.65	10.8
Normalized Emittance (ϵ_n), μm-rad	6.79	8.21	10.2
Ion Kinetic Energy, (E_i), GeV	10.12	11.46	13.24
Pulse Repetition Frequency, hertz	10	5	2.5
64 to 16 beamlet transition voltage (V_c), MV	133	160	180
ϵ_n/σ, μm-rad/degree, $V<V_c$	1.1	0.82	1.1
Depressed Tune (σ), $V>V_c$, degrees	7.5	10.5	10.0
Total Cost, M$ (1979)	552	633	749
Total Cost, M$ (1985)	715	788	911
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

splitting of the beamlets can lead to an unacceptable loss of beam brightness at final focus.

CONCLUSIONS

The cost and performance of the accelerators to produce a given target yield using mass 133, charge state +2 ions is very close to that using mass 200, charge state +3 ions. The final focussing requirements for the mass 133, charge state +2 are more demanding than that for the mass 200, charge state +3 ions. Beamlet splitting may be required to satisfy the final focussing requirements for the driver using the mass 133, charge state +2 ions.

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