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HEAVY-ION FUSION SYSTEM ASSESSMENT PROJECT Quarterly Status Report, April 1 - June 30, 1985.

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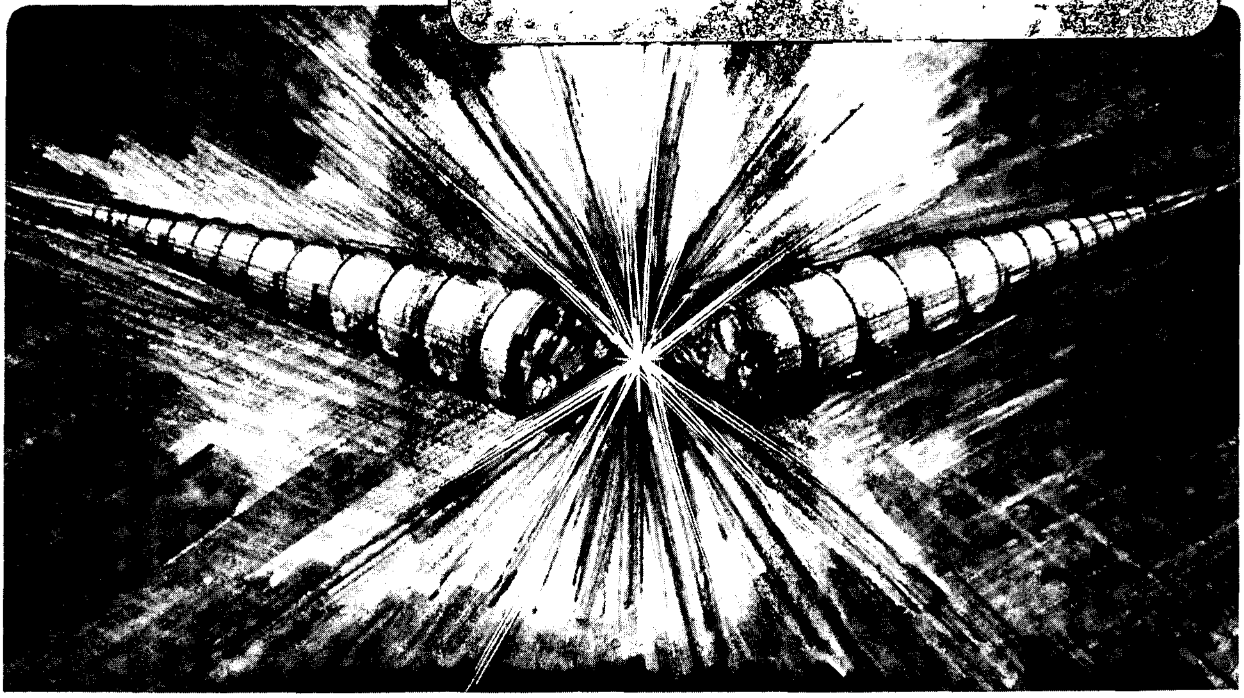

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HEAVY-ION FUSION SYSTEM ASSESSMENT PROJECT*

Quarterly Status Report, Apr.-Jun. 1985

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ACCELERATOR SYSTEM MODELING

1. The Cost Optimization Code LIACEP

1.1 Code Modifications

The cost optimization code LIACEP has been modified to operate on the VAX(8600) computer. The code requires from 3½ to 5½ minutes of CPU time per design case. This compares with CPU times of 1 to 1½ minutes per design case on the CDC 7600.

The tune-shift tables in LIACEP have been replaced by the analytic approximation formulated by Lee et al.(1) A comparison of the accumulative costs and efficiency of a 3 MJ drive, based on code runs using the analytical approximation vs. the tune-shift tables, is given in Table 1. The analytic approximation overestimates the cost by about 4.3% at 50 MV and underestimates the cost by 0.8% at 2500 MV. The total cost is underestimated by only 0.08% using the analytic approximation for the tune-shift tables.

More than 100 runs have been made with LIACEP since these changes were made. Most of these runs have been in support of the Heavy Ion Fusion System Assessment Project.

Table I. Comparison of a Cost and Efficiency Analysis of an Induction Linear Accelerator Using an Analytic Approximation with Tune-Shift Tables.

A = 200 amu
ϵ_n = 1.17×10^{-5} m-radians
N = 4 beams
q = $^{+}1$
f = 1 hertz
$\sigma_o = 60°$, $\sigma = 24°$
Superconducting quadrupoles, amorphous iron cores.
$I\tau$/beamlet = 75μ Coulombs
Ratio of cumulative costs and efficiency: (Analytic/Tables)

Voltage, MV	Cost Ratio	Efficiency
50.0	.0	.0
100.0	1.030	1.000
250.0	1.013	0.9949
500.0	1.007	0.9960
1000.0	1.004	1.000
2500.0	1.001	0.9942
5000.0	0.9987	0.9927
10000.0	0.9991	0.9966

1.2 Calculations for the Heavy Ion Fusion System Assessment

An early assessment of the optimized cost of the high energy end of induction linear accelerator was made for 200 amu ions with a charge state of +1, an input ion energy of 50 MeV and an output ion energy of 10 GeV. The accelerator had a normalized emittance of 1.17×10^{-5} m-radians for each of the 4 beamlets. The focussing element consisted of superconducting quadrupoles and the acceleration cores are of amorphous iron. The initial tune for these cases is 60°, while the depressed tune is 24°. For a pulse repetition frequency of 5 hertz, the cost is well approximated by a constant plus a term which varies linearly with the beam energy.*

$$C_{f=5,E} \propto E + 2.9 \qquad 1 \leq E \leq 10 \text{ MJ}$$

For an output beam energy of 3 MJ, the cost varies similarly with the pulse repetition frequency

$$C_{E=3,f} \propto f + 112 \qquad 1 \leq f \leq 10 \text{ hertz}$$

Thus the cost of this heavy ion induction linear accelerator is a much stronger function of the output beam energy than the pulse repetition frequency. The efficiency of the accelerator defined as the ratio of the output beam power, P, to the electrical power into the accelerator is given as

$$\eta \approx 5.1 P^{1/2} \qquad P \leq 11.8 \text{ MW}_B$$

$$\eta \approx 10.7 P^{1/5} \qquad P > 11.8 \text{ MW}_B$$

where the output beam power $P = Ef$, where f is the pulse repetition frequency in hertz and E is the total beam output energy in MJ. We also varied the

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* This scaling of cost with energy appears more adverse than it actually is in an optimized driver (where $C \propto E^{.4}$) due to the constraint on normalized emittance.

number of beamlets, and found the minimum cost case was between 4 and 16 beamlets, as shown in Table II. The minimum cost case at 8 beamlets is only 3.5% less than the cost of 4 beamlets.

Table II. Cost and Efficiency as a Function of Number of Beamlets for 3 MJ Driver.

$A = 200$ amu
$\epsilon_n = 1.17 \times 10^{-5}$ m-radians
$q = +1$
$f = 5$ hertz
$\sigma_o = 60°$, $\sigma = 24°$
Superconducting quadrupoles, amorphous iron cores
Initial Ion Energy = 50 MeV
Final Ion Energy = 10 GeV

Number of Beamlets	Cost	Efficiency, %
1	1.585	18.42
4	1.000	18.33
8	0.9659	21.58
16	1.009	19.87

TABLE III. Accelerator Parameter Space Investigated for Heavy-Ion Fusion System Assessment.

Ion Mass	130, 160, 190, 210 amu
Ion Kinetic Energy	5, 10, 15, 20 GeV
Beam Energy	1, 2, 3, 5, 10 MJ
Emittance	1.5×10^{-5}, (3×10^{-5})* m-radians
Pulse Repetition Frequency	5, (10), (15), (20)* hertz
Number of Beamlets	4, (8), (16)*
Ion Charge State	+1
Tune: 60°, Depressed Tune: 24°**	
Initial Ion Kinetic Energy	50 MeV
Focussing System:	Superconducting Quadrupoles
Core Material:	Amorphous Iron

*( ) - not completed

** Recent experiments show that a depressed tune of 8° can be achieved. This will lead to cost savings.

The parameter space investigated to date for the Heavy Ion System Assessment Project is given in Table III. The emittance of 1.5 x 10^{-5} m-radians was selected to give a spot radius on target of 1 mm, due to emittance, and allowing an effective spot radius of 2 mm due to the additional effects of momentum spread, and various aberrations in the final transport and focussing system. The selection of an initial tune of 60° and a depressed tune of 24° is arbritrary, as larger initial tunes and smaller depressed tunes have been achieved in the laboratory.

The cost and efficiencies of the accelerator system with an initial ion energy of 50 MeV are given in Tables IV through VII for various ion energies and beam energies. The costs are shown in Figures 1 through 4. All the costs have been normalized because the current costs for material and labor have not yet been included in LIACEP. In addition, an appropriate parameter space has not yet been identified on which to focus further analysis. Upon identification of an appropriate parameter space, a point design will be made, including a layout of the accelerator modules, which will suggest cost saving techniques and better cost estimates. However, the present analysis is adequate for determining a design parameter space.

For a given total beam energy W, there is an ion energy for which the normalized cost of the accelerator system is minimized as shown in Tables IV through VII and in Figures 1 through 4. The accelerator efficiency is maximized at the same points the cost is minimized. The reason for the cost minimum is that the accelerator cost increases with voltage and increases with charge, but the charge decreases with an increase in voltage for a given total beam energy. In addition, for a fixed output emittance, the normalized emittance of the accelerator increases with output voltage, and the cost of the accelerator with a fixed output voltage and beam energy and species will decrease with an increase of the normalized emittance.

TABLE IV. Normalized Cost & Efficiency of A=130 amu, 4 Beamlet Accelerator System with f=5 hertz, ϵ = 1.5 x 10^{-5} m-radians, q = +1, and a Tune of 60°-24°, with Superconducting Quads and Amorphous Iron Cores.

Normalized Cost

ε_i, GeV	5	10	15	20
ϵ_n, m-rad	4.34 x 10^{-6}	6.20 x 10^{-6}	7.67 x 10^{-6}	8.94 x 10^{-6}
W, MJ				
1	0.9415	0.7945 ⇐	0.8697	0.9925
2	1.550	1.114	1.094 ⇐	1.171
3	2.091	1.419	1.308 ⇐	1.335
5	3.277	1.993	1.699	1.645 ⇐
10	6.045	3.322	2.604	2.342 ⇐

(⇐ Minimum)

Efficiency, %

ε_i, GeV	5	10	15	20
ϵ_n, m-rad	4.34 x 10^{-6}	6.20 x 10^{-6}	7.67 x 10^{-6}	8.94 x 10^{-6}
W, MJ				
1	9.50	10.53 ⇐	8.72	6.80
2	10.86	13.92	13.84 ⇐	12.03
3	10.41	16.02	16.43 ⇐	15.40
5	11.16	17.67	19.75	19.36 ⇐
10	10.93	18.65	23.11	23.61 ⇐

(⇐ Maximum)

TABLE V. Normalized Cost & Efficiency of A=160 amu, 4 Beamlet Accelerator System with f=5 hertz, $\epsilon = 1.5 \times 10^{-5}$ m-radians, q = +1, and a Tune of 60°-24°, with Superconducting Quads and Amorphous Iron Cores.

Normalized Cost

ε_i, GeV	5	10	15	20
ϵ_n, m-rad	3.90×10^{-6}	5.57×10^{-6}	6.87×10^{-6}	8.00×10^{-6}
W, MJ				
1	1.036	0.8426 ⇐	0.9038	1.018
2	1.716	1.201	1.158 ⇐	1.225
3	2.344	1.537	1.394 ⇐	1.405
5	3.696	2.190	1.828	1.749 ⇐
10	6.796	3.720	2.863	2.514 ⇐

(⇐ Minimum)

Efficiency, %

ε_i, GeV	5	10	15	20
ϵ_n, m-rad	3.90×10^{-6}	5.57×10^{-6}	6.87×10^{-6}	8.00×10^{-6}
W, MJ				
1	7.88	10.13 ⇐	8.39	6.81
2	8.77	13.41	13.21 ⇐	11.66
3	9.57	14.18	15.72 ⇐	15.11
5	10.14	16.41	18.56	18.91 ⇐
10	9.48	17.32	21.78	22.82 ⇐

(⇐ Maximum)

TABLE VI. Normalized Cost & Efficiency of A=190 amu, 4 Beamlet Accelerator System with f=5 hertz, $\epsilon = 1.5 \times 10^{-5}$ m-radians, q = +1, and a Tune of 60°-24°, with Superconducting Quads and Amorphous Iron Cores.

Normalized Cost

ε_i, GeV ϵ_n, m-rad W, MJ	5 3.58×10^{-6}	10 5.09×10^{-6}	15 6.28×10^{-6}	20 7.30×10^{-6}
1	1.109	0.884 ⇐	0.9390	1.043
2	1.878	1.282	1.216 ⇐	1.267
3	2.587	1.645	1.471 ⇐	1.467
5	4.052	2.383	1.946	1.841 ⇐
10	7.293	4.068	3.109	2.687 ⇐

(⇐ Minimum)

Efficiency, %

ε_i, GeV ϵ_n, m-rad W, MJ	5 3.58×10^{-6}	10 5.09×10^{-6}	15 6.28×10^{-6}	20 7.30×10^{-6}
1	7.52	9.75 ⇐	8.30	6.85
2	8.18	12.52	12.96 ⇐	11.31
3	8.72	13.65	14.76 ⇐	14.58
5	8.38	15.61	17.27	18.30 ⇐
10	8.93	16.38	19.64	22.17 ⇐

(⇐ Maximum)

TABLE VII. Normalized Cost & Efficiency of A=210 amu, 4 Beamlet Accelerator System with f=5 hertz, $\epsilon = 1.5 \times 10^{-5}$ m-radians, q = +1, and a Tune of 60°-24°, with Superconducting Quads and Amorphous Iron Cores.

Normalized Cost

ε_i, GeV	5	10	15	20
ϵ_n, m-rad	3.40×10^{-6}	4.84×10^{-6}	5.96×10^{-6}	6.93×10^{-6}
W, MJ				
1	1.155	0.9197 ⇐	0.9573	1.060
2	1.980	1.334	1.251 ⇐	1.293
3	2.740	1.722	1.519 ⇐	1.504
5	4.293	2.507	2.027	1.896 ⇐
10	7.724	4.313	3.267	2.804 ⇐

(⇐ Minimum)

Efficiency, %

ε_i, GeV	5	10	15	20
ϵ_n, m-rad	3.40×10^{-6}	4.84×10^{-6}	5.96×10^{-6}	6.93×10^{-6}
W, MJ				
1	7.33	9.60 ⇐	8.27	6.97
2	7.87	12.23	12.73 ⇐	11.21
3	8.31	13.25	14.49 ⇐	14.38
5	7.76	13.94	17.03	17.83 ⇐
10	8.53	15.74	18.86	21.56 ⇐

(⇐ Maximum)

Figure 1.

Accelerator Cost as a Function of Energy for Various 130 amu Ion Energies

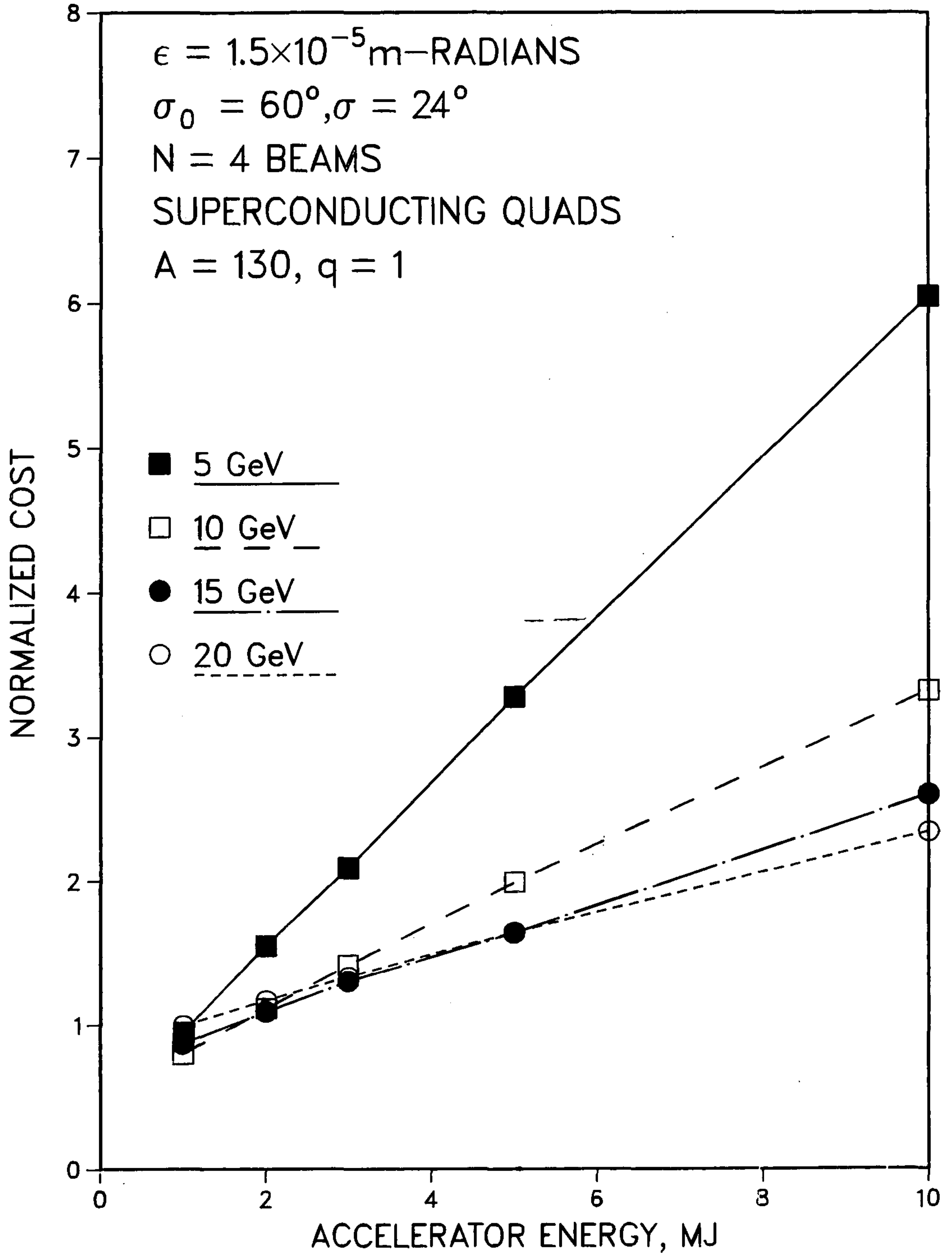


Figure 2.

Accelerator Cost as a Function of Energy for Various 160 amu Ion Energies

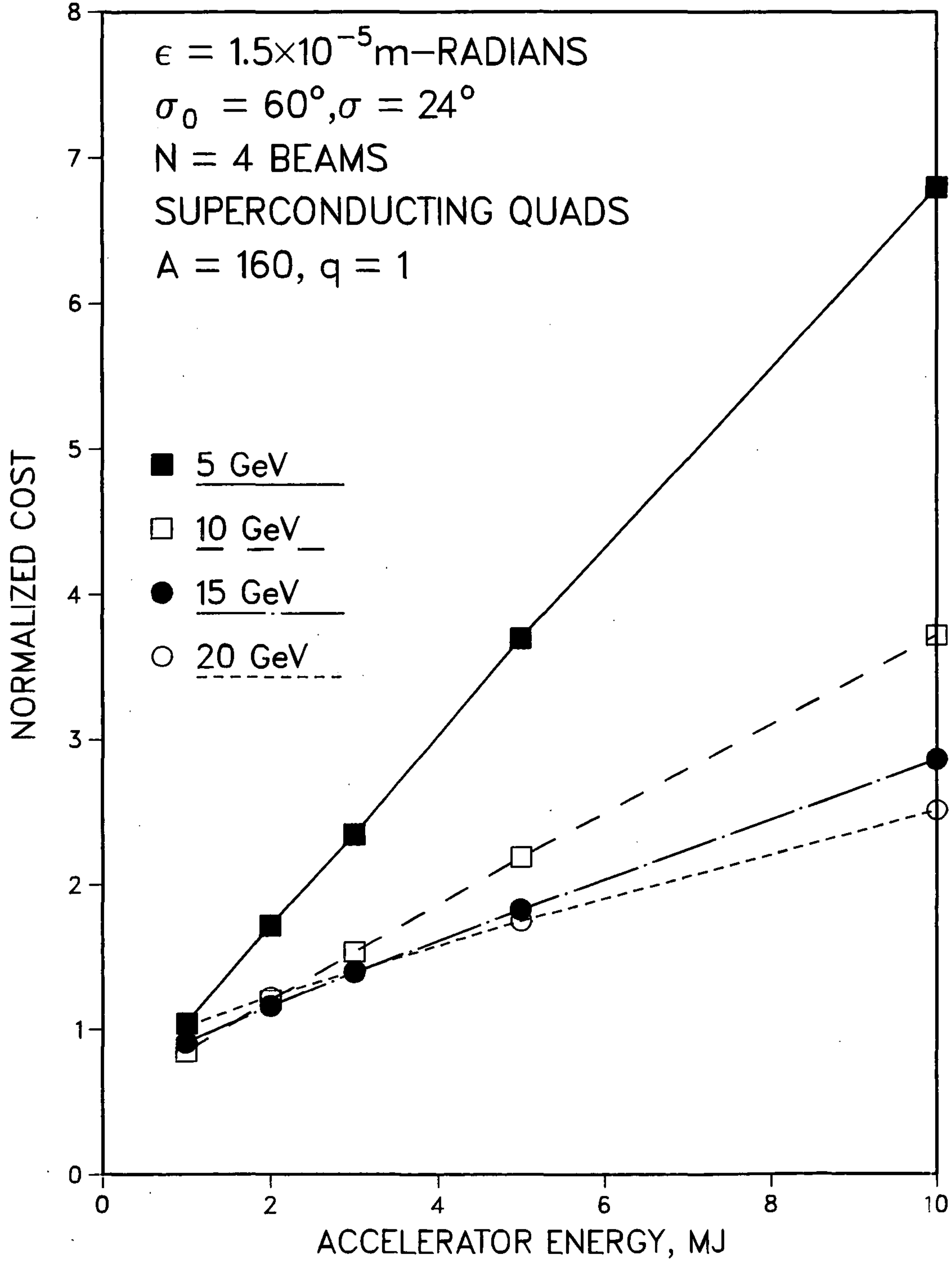


Figure 3.

Accelerator Cost as a Function of Energy for Various 190 amu Ion Energies

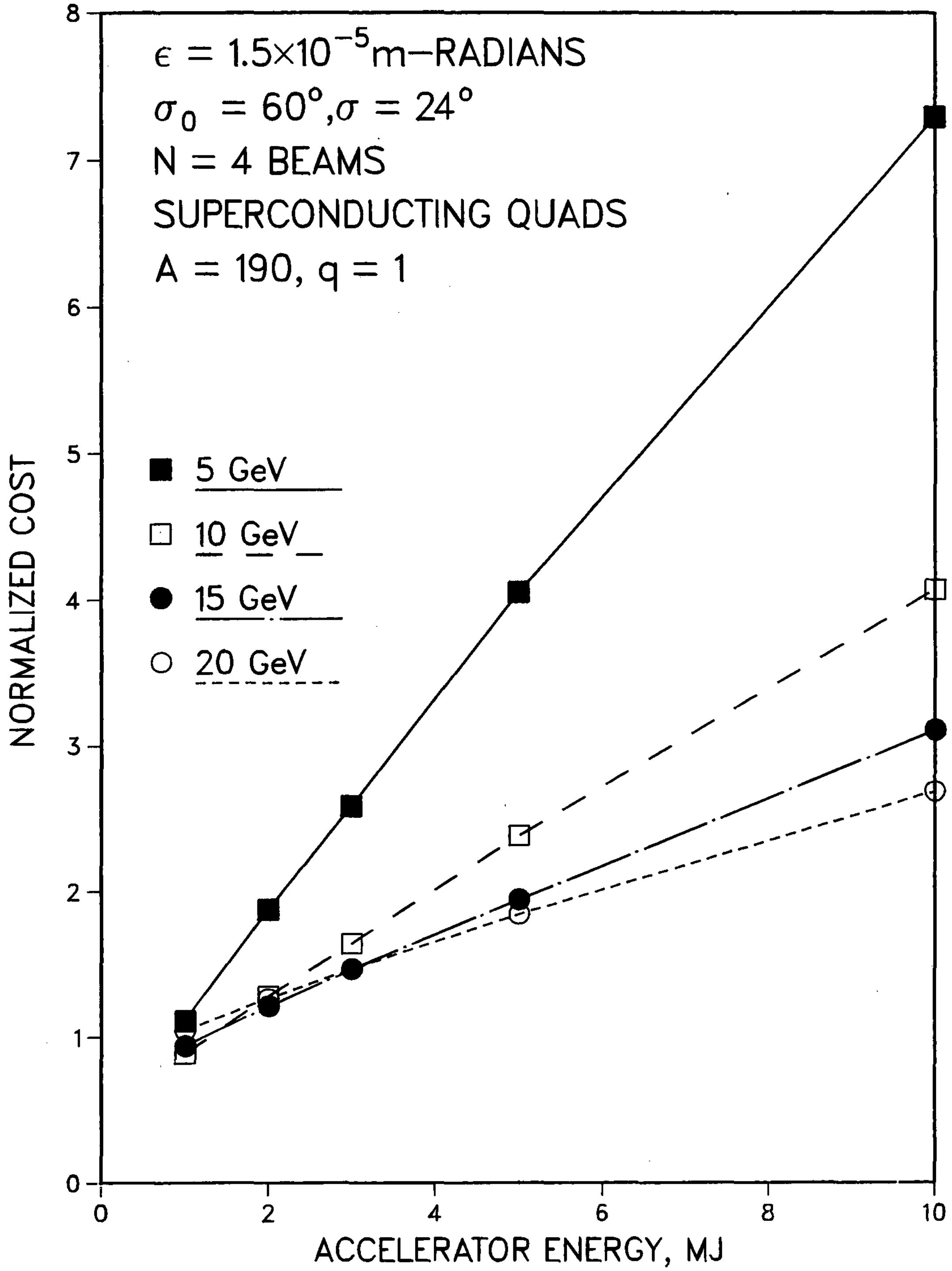
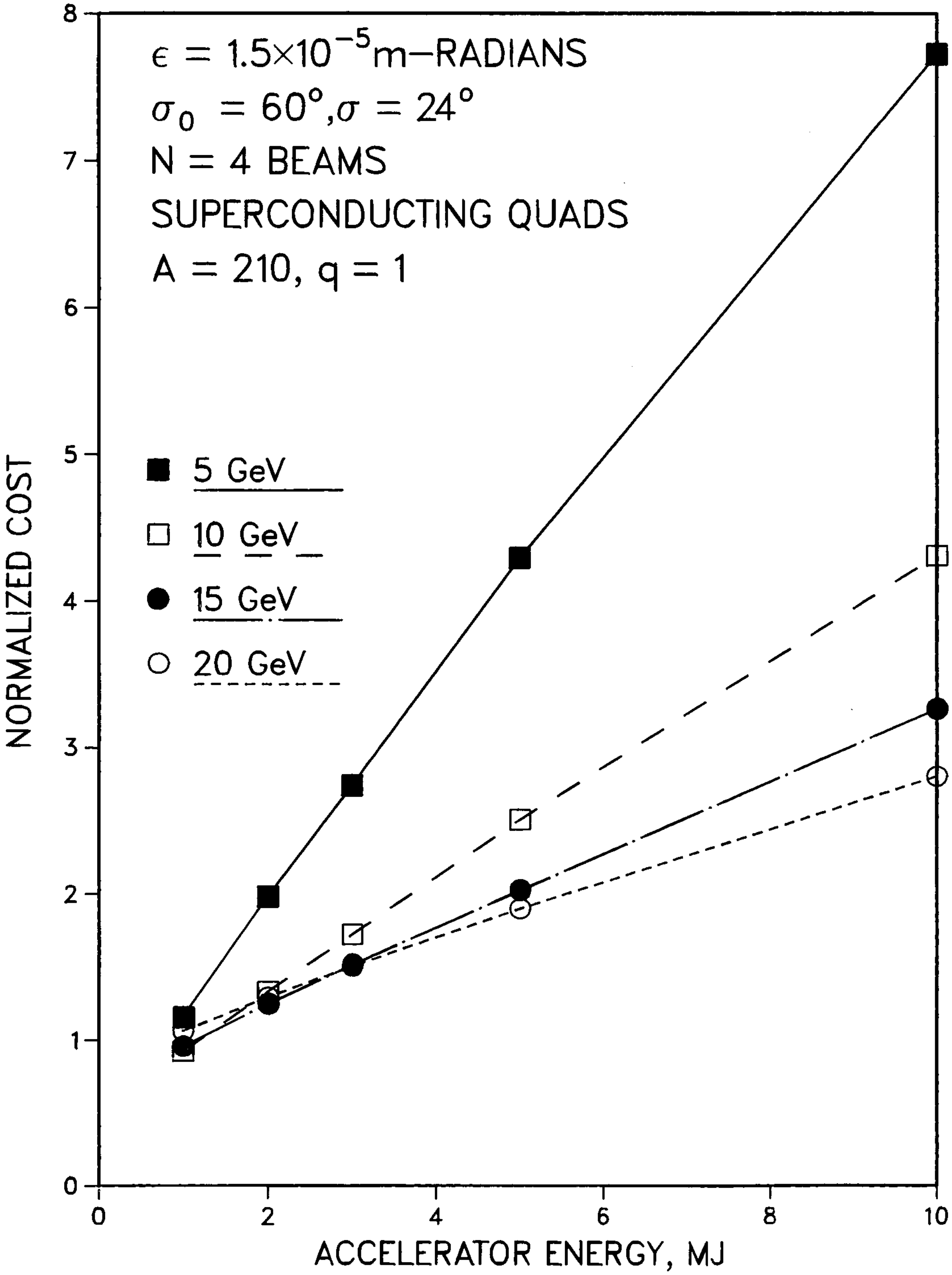


Figure 4.

Accelerator Cost as a Function of Energy for Various 210 amu Ion Energies



1.3 Post-Processor Code

A post-processor code has been developed to place LIACEP results in an accelerator-target design parameter space. For a given ion species and kinetic energy, the code calculates the range based on the range-energy curves of Bangerter, Mark, and Thiessen.(2) The spot radius is calculated from the beam output emittance, angle of convergence and a factor which accounts for the momentum spread and chromatic aberration in the beam and final focussing lenses. The spot size r and the range R formed into a $r^{3/2}R$ parameter and the total beam energy W are used to calculate the target gain based on the Lindl-Mark target gain curves(3) Using the results from LIACEP, the fusion power per unit accelerator cost and the ratio of fusion power to power into the accelerator can be determined and compared to other ion species, kinetic energy, and beam energy cases.

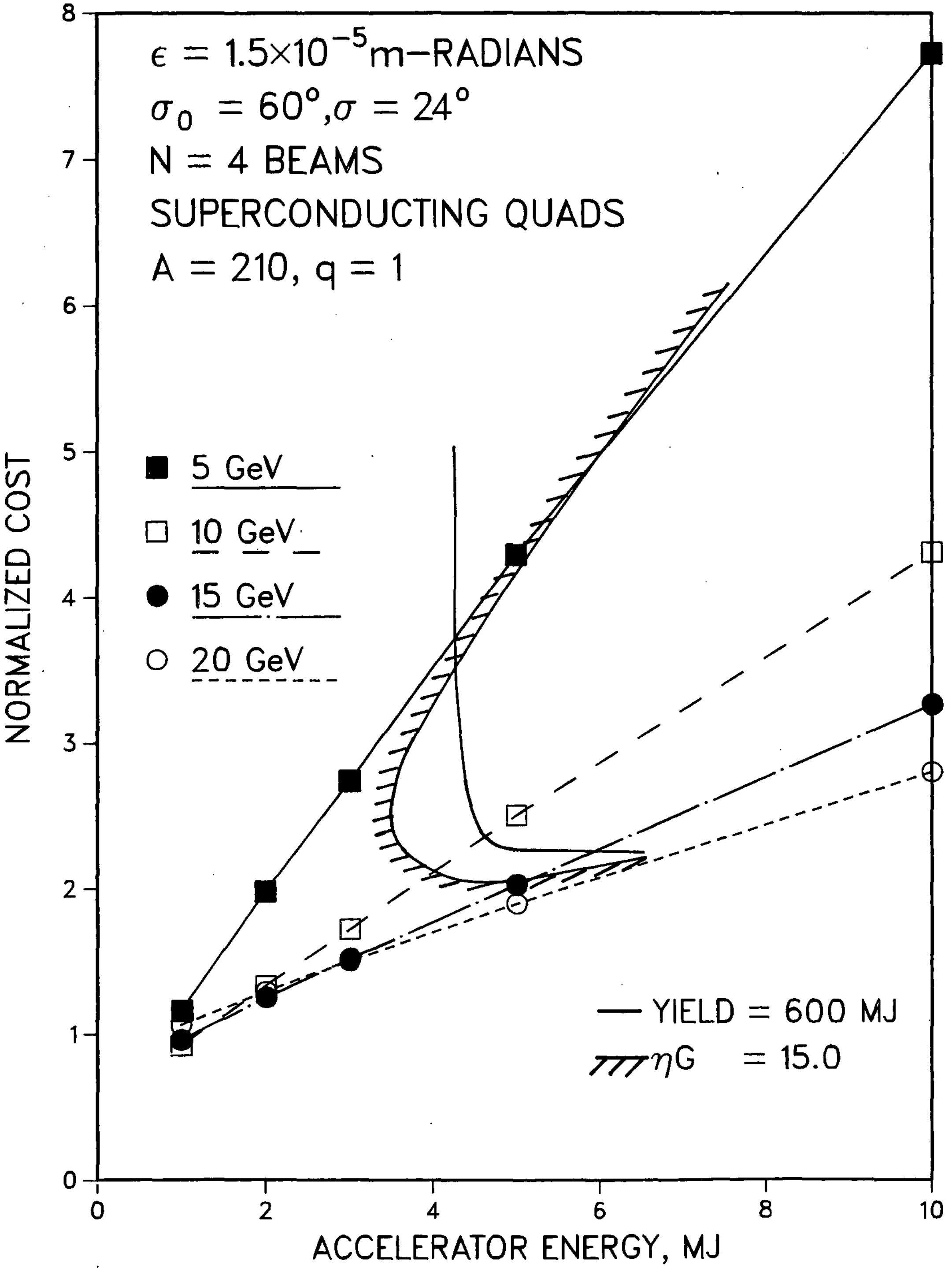
The post processor code results can then be plotted on the cost-beam energy parameter space given in Figures 1 through 4. An example is shown in Figure 5 for A = 210, $\epsilon = 1.5 \times 10^{-5}$ m-radians, and a spot size of 2 mm radius, where the constant ratio of fusion power to power into the accelerator (ηG) of 15 is plotted as a function of ion kinetic energy and beam energy. For the simultaneous satisfaction of $\eta G = 15$ and yield of 600 MJ, an ion kinetic of about 6 GeV and a beam energy of 4.3 MJ or an ion kinetic energy of 21 GeV and a beam energy of 6.4 MJ is required, with the latter case being the low cost option. The most cost effective case for this example, for a target yield of 600 MJ, is for an ion kinetic energy of about 10 GeV and a beam energy of about 4.5 MJ, which results in an ηG of 18.5. Similar plots have been made for other ion species.

1.4 Current Activities

We are currently making more LIACEP runs at an emittance of 3×10^{-5} m-radians in support of the HIFSA project. In addition, the post processor

Figure 5.

A Coupled Accelerator - Target Design Parameter Space for A = 210 amu with an unnormalized emittance of 1.5 x 10^{-5} m-radians and a spot radius of 2 mm; target yield of 600 MJ and $\eta G = 15$.



code is being modified for use as a pre-processor code to allow a more intelligent selection of the LIACEP input parameters that considers the target requirements for a given performance. We are in the process of modifying LIACEP to examine lower initial ion kinetic energies (from 50 MeV to 10 MeV). We are also studying the effects of changing the tune on the accelerator cost and efficiency.

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