LBL-20760
UC-34A

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Accelerator & Fusion Research Division

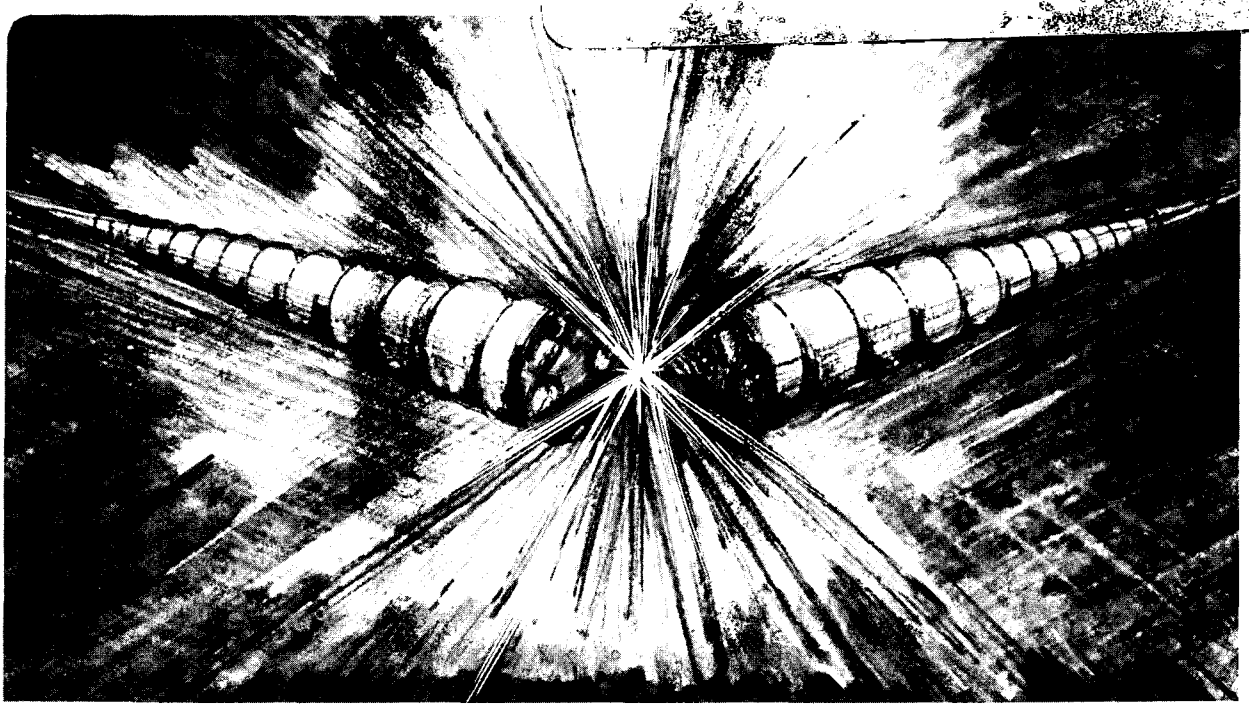
RECEIVED
LAWRENCE
BERKELEY LABORATORY
1986
LIBRARY AND

HEAVY-ION FUSION SYSTEM ASSESSMENT PROJECT:
Quarterly Status Report, July 1-September 30, 1985

E.P. Lee, J. Hovingh, and A. Faltens

September 1985

TWO-WEEK LOAN COPY
This is a Library Circulating Copy which may be borrowed for two weeks.



Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

LBL-20760 c.2

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

LBL-20760
HI-FAN-302

HEAVY-ION FUSION SYSTEM ASSESSMENT PROJECT*

Quarterly Status Report, Jul.-Sept. 1985

E. P. Lee, J. Hovingh, and A. Faltens

University of California
Lawrence Berkeley Laboratory
One Cyclotron Road
Berkeley, CA 94720

*Work performed under the auspices of the U.S. Department of Energy by Lawrence Berkeley Laboratory under contract DE-AC03-76SF00098. Funded by the Office of Program Analysis.

ACCELERATOR SYSTEM MODELING

1. Calculations for the Heavy Ion Fusion System Assessment

The parameter space investigated to date for the heavy ion system assessment project is given in Table I. The emittance of 3×10^{-5} m-radians was selected to give a spot radius on target of 2 mm due to emittance assuming the maximum convergence angle of 15 MV. The additional effects of momentum spread and various aberrations will increase the spot radius only by quadrature and are neglected here.

The normalized costs and the efficiencies of the accelerator system with an initial ion energy are given in Tables II through V for various ion energies (GeV) and beam energies (MJ). The normalized costs are shown in Figures 1 through 4.

2. Post-Processor Code Results for High Emittance LIACEP Calculations for the Heavy Ion Fusion System Assessment

The LIACEP results for the 3×10^{-5} m-radians transverse emittance cases were processed by the post-processor code and compared to the earlier 1.5×10^{-5} m-radians transverse emittance cases, assuming the same spot radius on target. The higher transverse emittance case resulted in about a 50% higher fusion power output per unit accelerator cost than the lower emittance case for the ($r^{3/2}R$, W) combination that results in a target gain at the upper bound of the best estimate gain curve. The ratio of fusion power to power into the accelerator (ηG) increases about 10% over the lower emittance case. For gains below the upper bound of the best estimate gain curve, the fusion power per unit accelerator cost advantage of the higher emittance case is

TABLE I. 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.

TABLE II. Normalized Cost & Efficiency of A=130 amu, 4 Beamlet Accelerator System with f=5 hertz, $\epsilon = 3. \times 10^{-5}$ 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	8.679×10^{-6}	1.24×10^{-6}	1.533×10^{-6}	1.78×10^{-6}
W, MJ				
1	0.6568 ⇐	0.6680	0.8027	0.9906
2	1.019	0.8593 ⇐	0.9514	1.089
3	1.360	1.049 ⇐	1.077	1.200
5	2.019	1.395	1.324 ⇐	1.391
10	3.625	2.226	1.892	1.851 ⇐

(⇐ Minimum)

Efficiency, %

ε_i, GeV	5	10	15	20
ϵ_n, m-rad	8.679×10^{-6}	1.24×10^{-6}	1.533×10^{-6}	1.78×10^{-6}
W, MJ				
1	12.97 ⇐	11.45	8.37	6.03
2	14.99	16.44 ⇐	14.20	11.54
3	15.59	19.47 ⇐	17.92	15.68
5	15.89	22.09	22.52 ⇐	20.80
10	17.15	24.73	27.15 ⇐	27.02

(⇐ Maximum)

TABLE III. Normalized Cost & Efficiency of A=160 amu, 4 Beamlet Accelerator System with f=5 hertz, $\epsilon = 3. \times 10^{-5}$ 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	7.808×10^{-6}	1.113×10^{-6}	1.374×10^{-6}	1.6×10^{-6}
W, MJ				
1	0.7109	0.6970 ⇐	0.8252	1.008
2	1.114	0.9121 ⇐	0.9911	1.126
3	1.502	1.123	1.131 ⇐	1.245
5	2.242	1.513	1.405 ⇐	1.458
10	4.100	2.457	2.046	1.956 ⇐

(⇐ Minimum)

Efficiency, %

ε_i, GeV	5	10	15	20
ϵ_n, m-rad	7.808×10^{-6}	1.113×10^{-6}	1.374×10^{-6}	1.6×10^{-6}
W, MJ				
1	11.20 ⇐	11.15	8.29	6.15
2	13.13	15.88 ⇐	13.98	11.64
3	14.40	18.16 ⇐	17.56	15.66
5	14.43	20.96	21.76 ⇐	20.62
10	15.90	23.29	26.19 ⇐	26.13 ⇐

(⇐ Maximum)

TABLE IV. Normalized Cost & Efficiency of A=190 amu, 4 Beamlet Accelerator System with f=5 hertz, ϵ = 3. 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	7.156 x 10^{-6}	1.019 x 10^{-6}	1.296 x 10^{-6}	1.461 x 10^{-6}
W, MJ				
1	0.7570	0.7252 ⇐	0.8407	1.024
2	1.203	0.9634 ⇐	1.026	1.159
3	1.636	1.192	1.181 ⇐	1.286
5	2.478	1.622	1.481 ⇐	1.523
10	4.490	2.667	2.197	2.068 ⇐

(⇐ Minimum)

Efficiency, %

ε_i, GeV	5	10	15	20
ϵ_n, m-rad	7.156 x 10^{-6}	1.019 x 10^{-6}	1.256 x 10^{-6}	1.461 x 10^{-6}
W, MJ				
1	10.67	10.90 ⇐	8.44	6.27
2	12.56	15.22 ⇐	13.92	11.60
3	13.65	17.37 ⇐	17.21 ⇐	15.55
5	13.39	20.32	21.30 ⇐	20.26
10	13.16	22.45	25.51 ⇐	25.67 ⇐

(⇐ Maximum)

TABLE V. Normalized Cost & Efficiency of A=210 amu, 4 Beamlet Accelerator System with f=5 hertz, $\epsilon = 3. \times 10^{-5}$ 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	6.802×10^{-6}	9.68×10^{-6}	1.193×10^{-6}	1.386×10^{-6}
W, MJ				
1	0.7879	0.7440 ⇐	0.8609	1.040
2	1.260	0.9933 ⇐	1.050	1.179
3	1.725	1.235	1.214 ⇐	1.316
5	2.628	1.699	1.527 ⇐	1.567
10	4.719	2.824	2.288	2.140 ⇐

(⇐ Minimum)

Efficiency, %

ε_i, GeV	5	10	15	20
ϵ_n, m-rad	6.802×10^{-6}	9.68×10^{-6}	1.193×10^{-6}	1.386×10^{-6}
W, MJ				
1	10.44 ⇐	10.37 ⇐	8.40	6.35
2	12.14	15.01 ⇐	13.85	11.65
3	13.09	16.89	17.01 ⇐	15.50
5	12.82	18.93	20.91 ⇐	19.93
10	12.73	21.78	24.78	25.39 ⇐

(⇐ Maximum)

Figure 1.

Accelerator Cost as a Function of Energy for Various 130 amu Ion Kinetic Energies with an unnormalized Emittance of 3 x 10^{-5} m-radians

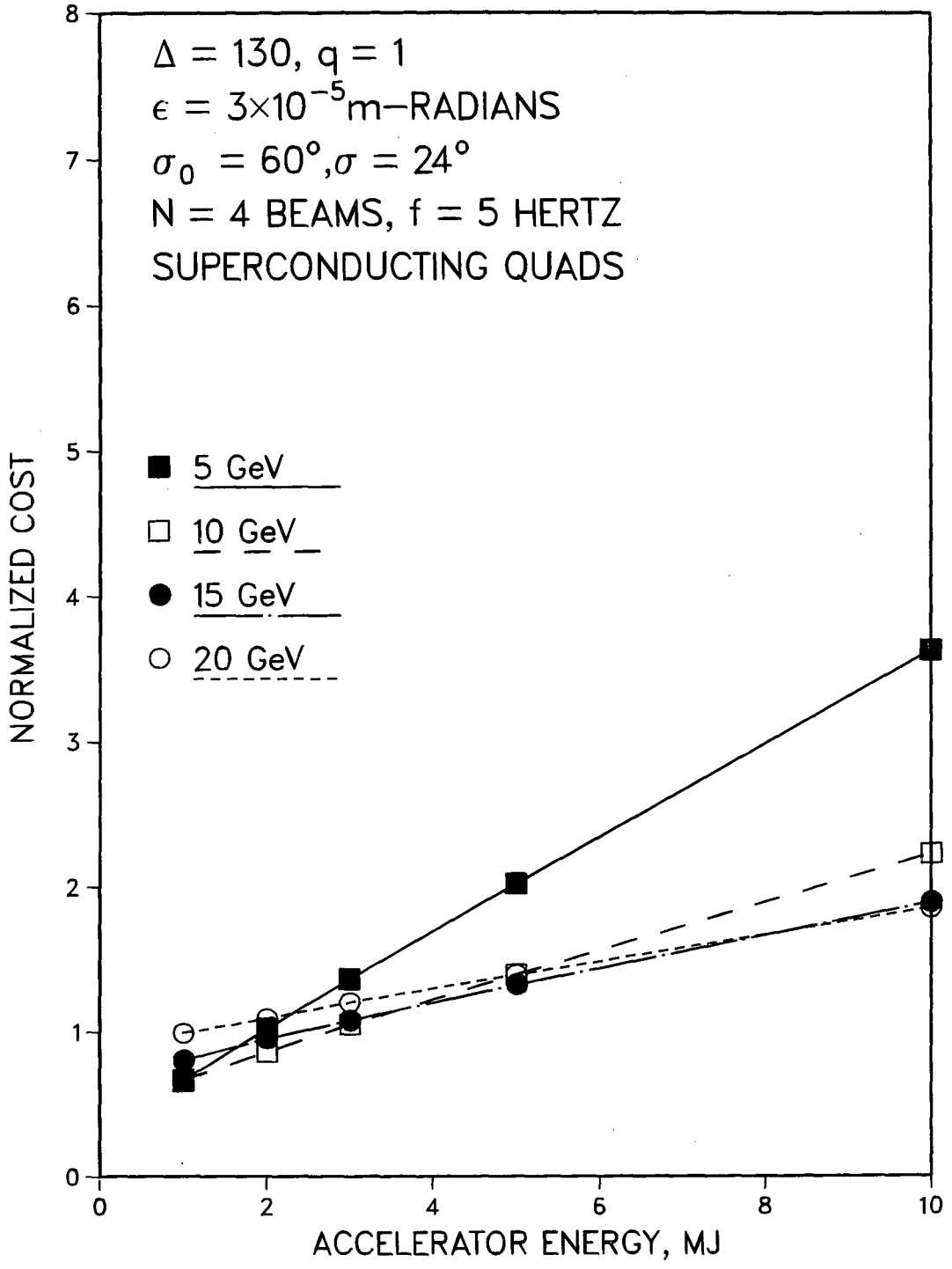


Figure 2.

Accelerator Cost as a Function of Energy for Various 160 amu Ion Kinetic Energies with an Unnormalized Emittance of 3 x 10^{-5} m-radians

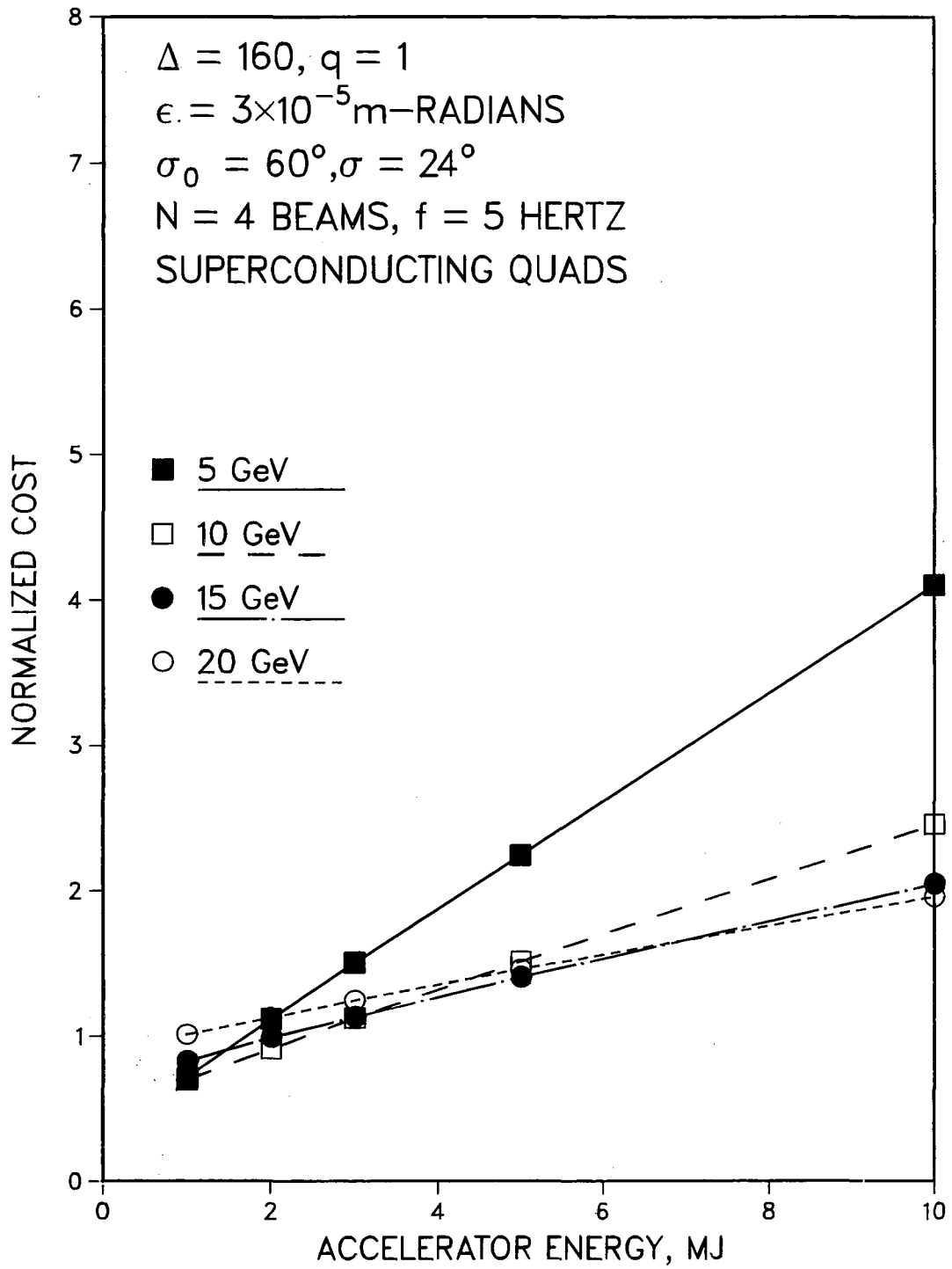


Figure 3.

Accelerator Cost as a Function of Energy for Various 190 amu Ion Kinetic Energies with an Unnormalized Emittance of 3 x 10^{-5} m-radians

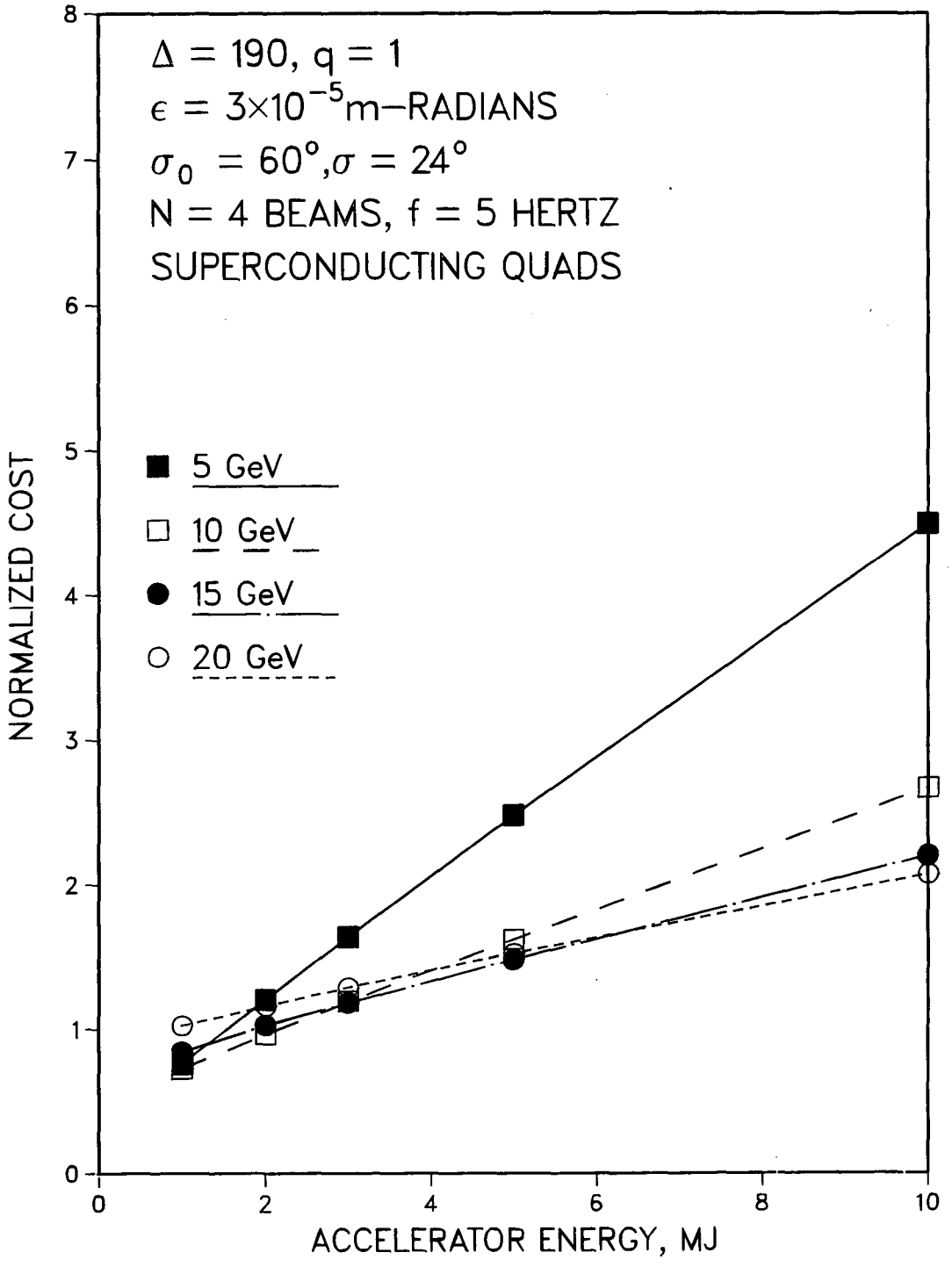
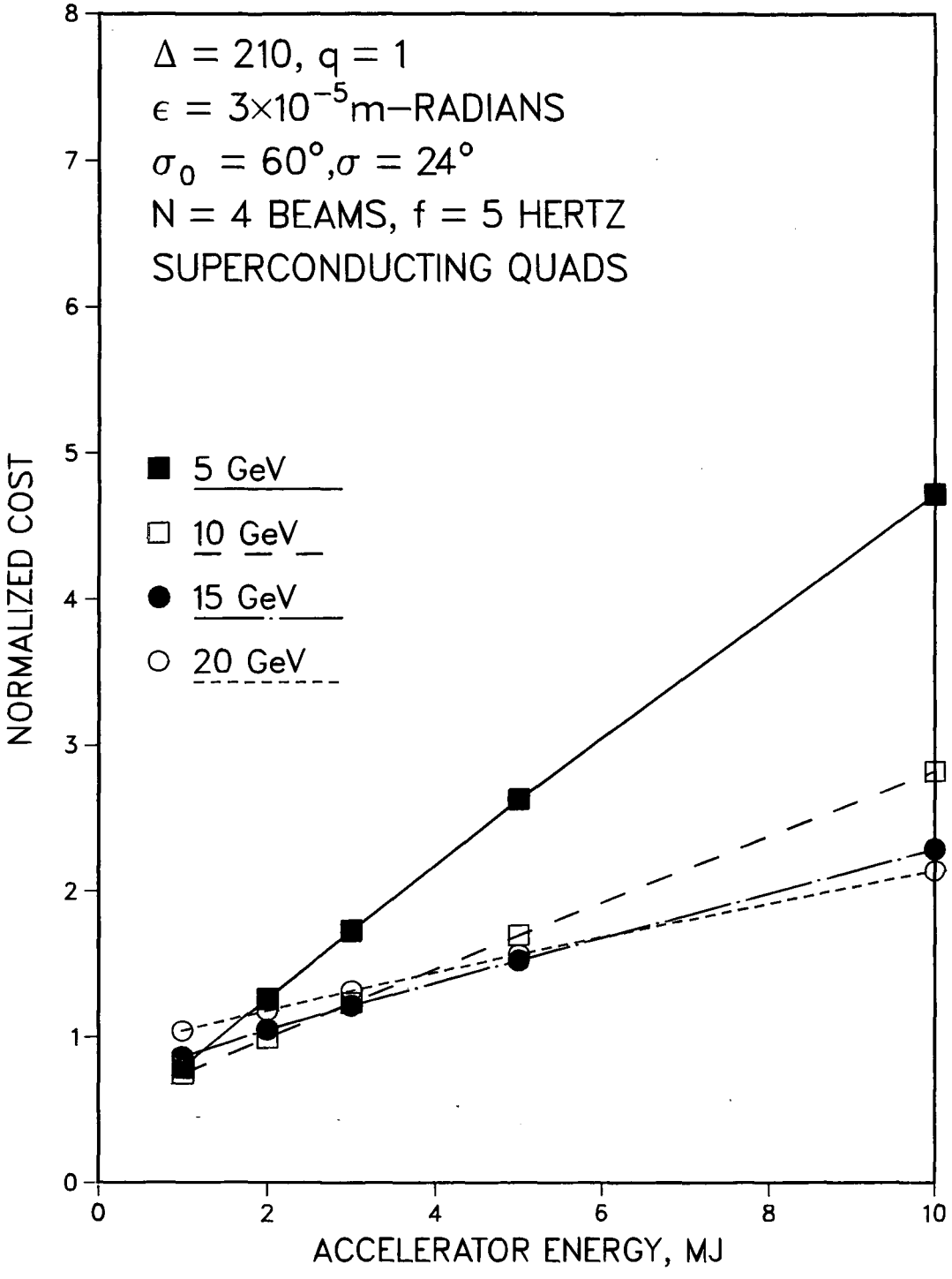


Figure 4.

Accelerator Cost as a Function of Energy for Various 210 amu Ion Kinetic Energies with an Unnormalized Emittance of 3 x 10^{-5} m-radians



reduced from that at the upper bound of the best estimate gain curve while the ηG advantage of the higher emittance case increases for gains less than the upper bound of the best estimate gain curve.

3. The Effect of Tune and Tune Shift on the Normalized Accelerator Costs

The effect of the tune and tune shift on the normalized costs of the 3 MJ accelerator producing 10 GeV, 200 amu ions described in Table VI, was investigated for a fixed normalized emittance of 1.17×10^{-5} m-radians. The normalized cost of this accelerator section from 50 MeV as a function of the tune σ_o for various depressed tunes σ is shown in Figure 5. For a given depressed tune σ, there is a tune σ_o that results in a minimum cost accelerator system. As the depressed tune σ decreases. the minimum cost system occurs at a lower tune σ_o for a fixed normalized emittance, and the minimum cost increases with a decrease in σ_o.

An additional finding is that for a given set of constraints on the accelerator design (maximum pole tip field, maximum beam radius, maximum longitudinal space charge factor, maximum half-period length to beam radius ratio), a minimum voltage can be determined for which a solution does not exist for a given combination of normalized transverse emittance, tune and depressed tune. In order for a solution to exist at lower voltages, the constraints used in the high voltage section must be relaxed, the tune decreased or the depressed tune increased for a fixed normalized transverse emittance, or preserving the constraints and tune conditions, the normalized transverse emittance must be decreased.

4. Pre-Processor Code

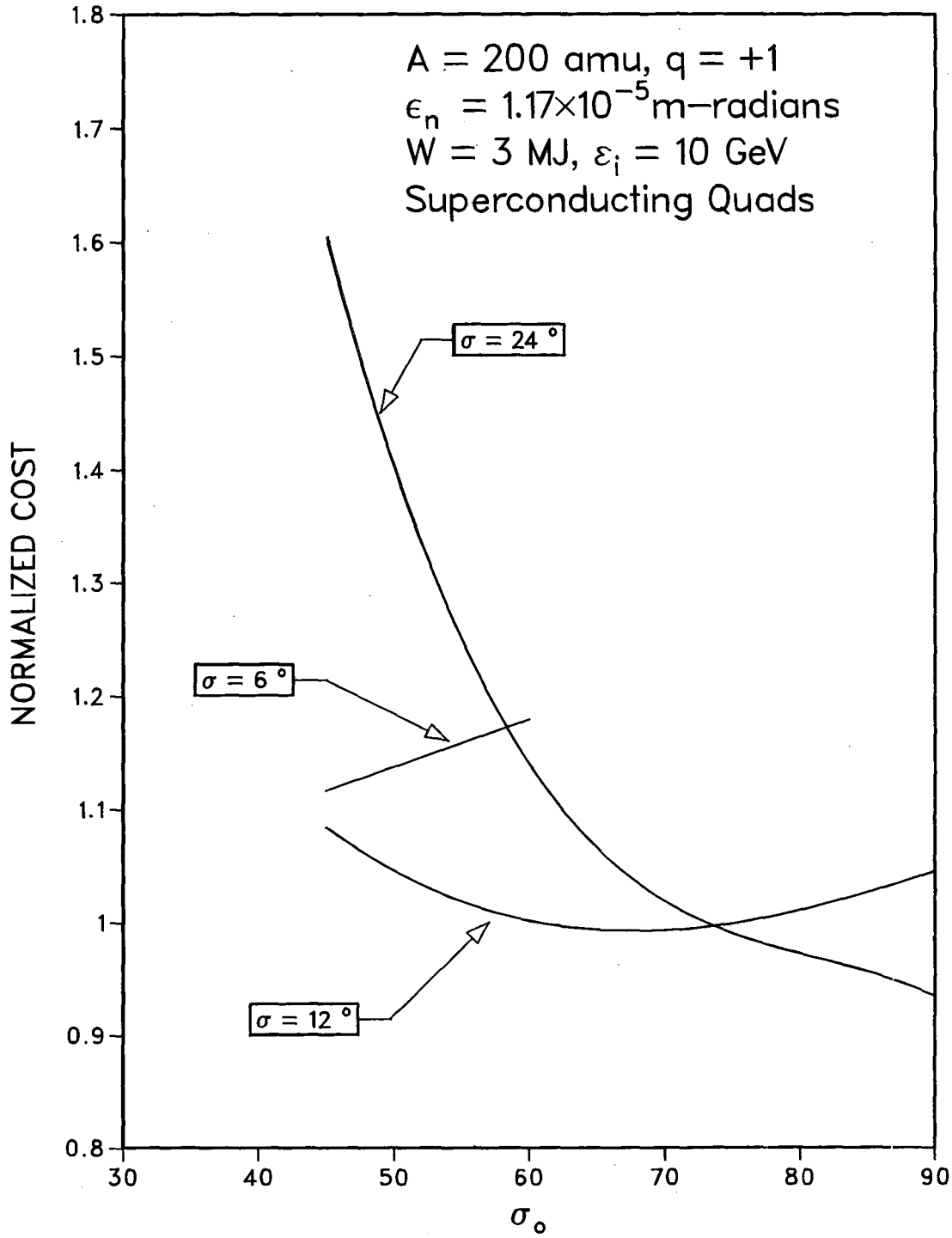
A pre-processor code to guide in the selection of combinations of driver energy W, emittance, and ion kinetic energy to achieve the upper bound of the best estimate region of the Lindl-Mark target gain curve was extracted from the post-processor code. This pre-processor code was used to select the required accelerator parameters for target yields of 300, 600, and 1200 MJ with spot size to output beam energy ratios of $r/W^{1/3}$ of 0.1, 0.15, and 0.2 which include the upper and lower bounds of spot size for which the Lindl-Mark target gain curves are valid.

TABLE VI. Accelerator Characteristics for Tune Depression Effects on Accelerator Costs.

Atomic Mass	200 amu
Ion Charge State	+1
Normalized Emittance	1.17×10^{-5} m-radians
Pulse Repetition Frequency	5 hertz
Number of Beamlets	4
Initial Ion Kinetic Energy	50 MeV
Final Ion Kinetic Energy	10 GeV
Accelerator Energy	3 MJ
Focussing System	Superconducting Quadrupoles
Core Material:	Amorphous Iron

Figure 5.

The Effect of Initial Tune and Depressed Tune on the Cost of a 3 MJ Accelerator of 200 amu Ions to 10 GeV With a Normalized Emittance of 1.17×10^{-5} m-radians



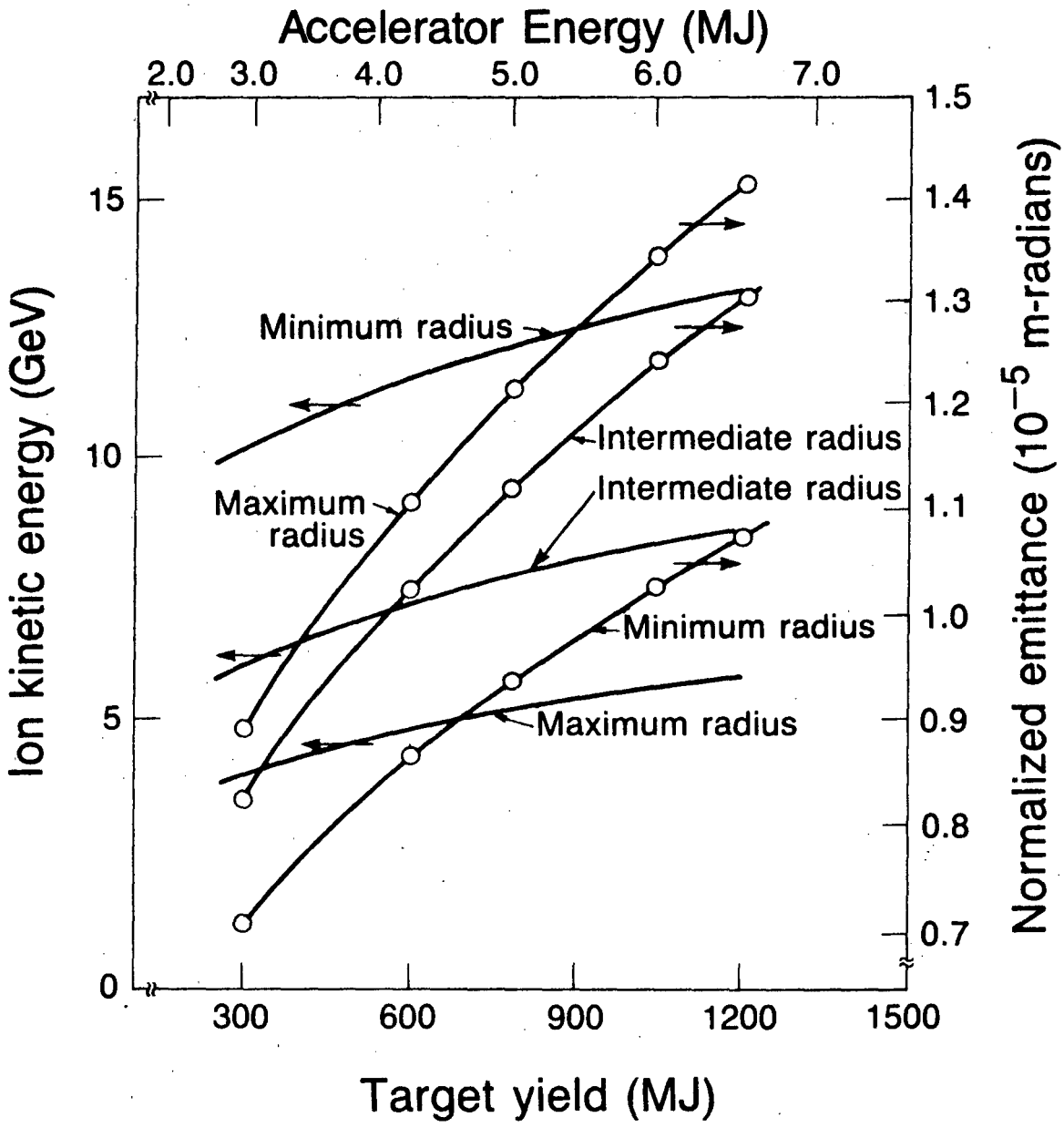
The normalized transverse emittance and the 200 amu ion output kinetic energy for several values of $r/W^{1/3}$ and the output beam energy W are shown in Figure 6 as a function of pellet yield. These cases will be analyzed using LIACEP for a tune shift of 75°-24° and for 4, 8, and 16 beamlets.

5. Current Activities

We are currently making more LIACEP runs at emittances of both 1.5×10^{-5} and 3×10^{-5} for pulse repetition frequencies of 10, 15, and 20 hertz for the 130 amu and the 210 amu ions. We are also in the process of examining the cases of 8 and 16 beamlets for these cases. In addition, we are making LIACEP runs for the cases described in Section 4.

Figure 6.

Accelerator Parameter Space as a Function of Target Yield for Several Target Spot Radii for Ion Mass 200 amu



XBL 8511-11517

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720