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YEAR-END-REPORT ON HEAVY-ION FUSION PROGRAM

Heavy Ion Fusion Staff

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LAWRENCE BERKELEY LABORATORY

YEAR-END-REPORT ON HEAVY-ION FUSION PROGRAM*

HIF STAFF

FISCAL YEAR 1978

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1. INTRODUCTION

The close of the Fiscal Year 1978 almost coincided in time with the Third Heavy Ion Fusion Workshop (Sept. 19-26, 1978), held this year at Argonne National Laboratory. In the preparation of this report we have therefore drawn heavily on some of the material and reports that were presented by the LBL HIF Staff at that workshop.

During the year a number of intensive work sessions of short duration took place on specific topics:

- Parameters for HIDE: Roger Bangerter, Edward Lee and Simon Yu, all from Lawrence Livermore Laboratory, helped greatly in defining the goals and parameters for a minimum HIDE. It was felt that with a beam energy of 30 kJ and a beam power of 3 TW, three goals could be met in the following order of importance: demonstration of accelerator performance, scaled beam-propagation experiments in low-pressure gases, and a target coupling experiment in slab geometry at a specific energy of 20 MJ/gm.
- A Synchrotron-based HIDE design: The scientific staffs of the SuperHILAC and Bevalac collaborated with us on an intensive two-week design effort to explore the possibility of a low-cost HIDE design based on a synchrotron and external induction linac buncher. A 5 TW, 50 kJ example using Bi^{+1} injected at 500 MeV and accelerated to 3.5 GeV was the focus of most of the study. The plan was to extract the beam in a single bunch--to be further bunched externally by induction modules--and thus avoid a multiplicity of final transport lines to the target. It is recognized that the lower the energy the

less attractive the synchrotron approach becomes, and at an energy of only 3.5 GeV it was apparent that no convincing solution could be found unless unduly optimistic assumptions were made about the ability to do bunching and debunching operations without dilution.

- A two-day Topical Workshop on the optics of the Final Focus was held on August 7 and 8, 1978, and there was outside attendance from ANL, BNL, and SLAC. The attendees, topics discussed and summary notes are given in Section 5.

During the year a computer link was established between the CDC7600 system at LBL and the TI-ASC system at the Naval Research Laboratory. This allows us to have direct access to the numerical simulation data of I. Haber and thus has added an important dimension to our collaboration with NRL. There is also a continuing fruitful collaboration with S. Penner at NBS, who has a simulation code of a different type.

We have benefitted by the one-year visit (ending July 1978) by Ingo Hofmann from the Max-Planck Institute for Plasma Physics, Garching, Germany, the continuing half-time collaboration of W. B. Herrmannsfeldt of SLAC, and the frequent interaction with R. O. Bangerter and his colleagues at LLL.

2. THE EXPERIMENTAL PROGRAM

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2.1 Introduction

The experimental efforts at LBL have been focused on both the development of a large aperture 2 MeV, 1A Cs^{+1} ion beam¹⁾ using contact ionization and drift tube techniques as an injector for an induction linac and, also, a 750 kV, 60 mA Xe^{+1} ion beam²⁾ using multiaperture accel-decel extraction and a Cockcroft-Walton accelerator high gradient column for an r.f. linac source.

2.2 The One-Ampere Cesium Source

A schematic diagram of the Cs^{+1} beam experiment is shown in Fig. 1. Neutral Cs atoms, generated either by heating metallic Cs or a ($\text{CsCl} + \text{Ca}$) mixture, are sprayed onto a hot iridium plate (anode) of 30 cm dia. which is at a temperature of 1200°K-1400°K. The ionization potential of Cs (3.9V) is smaller than the work function of iridium so that most of the Cs atoms are adsorbed on the anode surface as ions. The supply rate of Cs atoms is determined by the oven temperature and is designed in such a way that there is ~1% of a monolayer (1mC) of Cs accumulated on the anode when the extraction voltage pulse is applied to it. The Cs^{+1} ion emission rate is determined by the temperature and coverage of the iridium hot plate and is designed to be about 5 times the space charge limited current. In this space-charge limited operation the beam emission is uniform over the surface independent of the non-uniformities of the temperature of the anode and the neutral Cs flux.

The space-charge limited current is 1A for the extraction voltage of 500 kV which was applied to the anode. Emission-limited operation occurred when the anode temperature was below 1100°K in which case the Cs^{+1} current was independent of the applied voltage pulse and depended only upon the anode temperature.

Cs depletion was observed when the anode temperature was high and the neutral Cs supply was low. In this case all the available Cs ions were used up during the earlier part of the voltage pulse. The space-charge-limited condition was recovered when the oven temperature was increased in this case.

Beam neutralization could increase the current above the classical space charge limit. Our current measurement is not yet accurate enough to establish this because of the undetermined secondary electron correction. Although the secondary electron effect was measured to be small in our earlier Cs test stand experiment, we are building improved diagnostics to delineate the phenomenon.

Time-of-flight measurements, as shown in Figure 2, proved that virtually all of the beam was composed of Cs^{+1} ions. The beam also had orders of magnitude lower intrinsic neutral background pressure compared to any electron-bombardment ionization source. This is as expected since the Saha-Langmuir equation shows that more than 99% of the incident Cs atoms are ionized. The ion beam has a very low thermal velocity equal to the temperature of the anode (0.1 eV). It is thus very bright. Normalized emittance based on the thermal spread is calculated to be $\frac{\epsilon \beta \gamma}{\pi} = 0.006 \text{ cm-mrad}$. The final beam emittance will be determined by non-source-originated mechanisms such as lens aberrations and scattering by grids.

The source is now operating at a few μC capacity but it can be easily scaled up by increasing the extraction voltage (up to 1 MV) and the area of

Fig. 1: Schematic diagram of the Cs^{+1} beam experiment
(Drift tube lengths not to scale)

the anode. (The contact ionization source is also applicable to uranium.⁴⁾ Since the uranium ionization potential, approximately 6.3 volts, is higher than the work function of any refractory material, the anode needs to be oxidized or fluoridated to obtain a higher work function.) The extracted Cs^{+1} beam is focused by Pierce electrodes⁵⁾ (Fig. 3) and will be further accelerated by a three-section pulsed drift-tube, which is being assembled at the present time. The beam will gain an increment of 500 keV per stage and reach 2 MeV at the end of the drift tubes. Other experiments under consideration are: (1) an addition of accelerating stages using induction linac cavities, and (2) a strong-focusing transport experiment.

Fig. 2: Time of flight measurements of Cs^{+1} beam. Time was measured from the end of the voltage pulse and the end of the current pulse. L s are the distances of the drift space.

BBC 788-10359

Fig. 3: A photograph showing the iridium hot plate, the Pierce electrode, and insulator column of the Cs⁺¹ contact ionization source.

2.3 The 60 mA Xe⁺¹ Source

The Xe⁺¹ multiaperture source has been described in Ref. 2. The present source configuration utilizes an array of 13 holes each 4 mm in diameter symmetrically arranged within a 25 mm diameter circle. Development of this source was carried out in the Bevatron 20 kilovolt test stand.

A beam of 40 mA at 20 kV was transported one meter through a quadrupole triplet and measured with a biased Faraday cup. The measured beam diameter was 38 mm and the emittance was $\frac{\epsilon_n}{\pi} = \frac{\epsilon \beta \gamma}{\pi} = 0.03$ cm mrad. A 50-degree magnetic analysis showed the beam to contain 90% Xe⁺¹ charge state.

This source was then installed in the 750 kilovolt Cockcroft-Walton accelerator. The 20 kV Xe⁺¹ beam was transported one meter through two magnetic quadrupole triplets and accelerated to 500 kilovolts through the high gradient column.

A beam of 60 mA was measured with an electrically biased Faraday cup. This cup is also provided with a transverse magnetic field. The observed beam diameter was 38 mm.

The plasma arc was operated at 30 V and 50 A and a pulse length of 500 μ sec. These conditions are the same as on the 20 kilovolt test stand which yielded 90% Xe^{+1} .

A typical beam current pulse is shown in Figure 4.

Our computer calculations show that the two quadrupole triplets can only transport about 1 mA of un-neutralized Xe^{+1} . This implies that the initial beam is more than 98% neutralized.

Measurements of emittance and a magnet analysis of the beam are in progress. Following this the beam energy will be increased to 750 kV.

XBL 7811-14192

Fig. 4: 500 kV Xe^{+1} beam current vs. time

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 2. Reference 1, page 91.
 3. J. B. Taylor and I. Langmuir, Phys, Rev. 44. 423 (1933).
 4. M. Hashmi, A. J. Van der Houven van Oordt, Conference on U Isotope Separation, London, March 5-7 (1975).
 5. Designed by W. Herrmannsfeldt, SLAC.
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3. A CONCEPTUAL DESIGN AND COST PROCEDURE FOR HEAVY-ION INDUCTION LINACS

A. Faltens, E. Hoyer, D. Keefe and L. J. Laslett

3.1 Introduction and Background

For electrons, the induction linac has been well-established as a high-current (~ 1 kA) accelerator with high repetition rate, good electrical efficiency and high operational reliability (reference 1 contains an extensive list of references). In such systems the electrons are injected at relativistic speed so that pulse compression by differentially accelerating the head and tail of the beam bunch is not an available option; the beam current, I , and pulse duration τ , remain constant along the accelerator. The design procedure thus becomes one of designing a single accelerating module (appropriate to the chosen I and τ) and simply iterating such modules until the final beam particle energy (voltage) has been reached. (This is not to discount the fact that there are many options that must be examined; e.g., choices in ferromagnetic material, in stacking cores radially, in insulator configurations, etc., before arriving at the final design of the single basic unit).

For a non-relativistic ($\beta < 0.5$) heavy ion induction-linac driver, however, the design procedure is much less transparent. For instance, the particle mass and charge can have a range of values - also the final beam voltage, V_f , (kinetic energy/charge-state, q), is a matter of choice since only the product, $[I\tau]V_f = Q$, is specified for a driver delivering Q megajoules. A novel and most important degree of freedom is available in such a machine - namely, the ability to achieve pulse compression by modest differential acceleration (slightly-ramped voltage pulses); this comes at the price - to the designer - of allowing a free choice of beam current over a wide range at any point along the machine. The upper bound on current is set by the transverse space charge limit (equivalent to the so-called Maschke power-limit); on the lower side, while there is no physical bound, in general one finds that a decrease in current is accompanied by a decrease in electrical efficiency and an increase in cost.

The essence of our design procedure is to pick a specific total beam charge $[I\tau]$, one value in a sequence, and examine the differential cost, ΔC , required to add an increment of voltage $\Delta V = 1$ MV to the beam at each voltage point, V , along the accelerator. In general, there is a minimum value of $\Delta C/\Delta V$ at each voltage point, V , which in turn determines the exact design for the accelerating modules, pulsers and magnets at that point; if one seeks for example, a minimum-cost accelerator, the entire design is determined and the cost -- except for the injector and final beam manipulation sections -- is given by

$$\left[C_{\min} \right]_{[I\tau]} = \left[\int_{V_{\text{inj}}}^{V_f} \left(\frac{\Delta C}{\Delta V} \right)_{\min} dv \right]_{[I\tau]} \quad (1)$$

In most cases some departure from the minimum-cost design, particularly at the higher voltage points, is desirable for electrical efficiency reasons and for meeting the final longitudinal requirements. Thus it is important to have detailed information of the nature of the $\Delta C/\Delta V$ variation, i.e., whether it is a broad or narrow stationary minimum or if it is a non-stationary minimum arising from a constraint. See Fig. 1 for an example $\Delta C/\Delta V$ curve.

That, in principle, a stationary minimum for $\Delta C/\Delta V$ exists can be illustrated as follows. The volt-second requirements for the cores to add 1 MV is

$$\text{Volt-Secs} = 10^6 \tau = 10^6 \frac{[I\tau]}{I} \propto (I)^{-1} \quad (2)$$

Thus lower core and pulser costs can be achieved by arranging for the highest beam-current; this requires a high density of transport magnets (occupancy fraction, η , approaching unity). The current I attains its maximum value as $\eta \rightarrow 1$ but this leaves no space at all for the accelerating cores and the cost to add 1 MV tends to infinity. Conversely, the cost of the magnet system can be lower by operating at low beam-current (i.e., $\eta \rightarrow 0$) which in turn, from Eqn. 2, implies increased volt-seconds of core and likewise cost. Between these extremes there is an appropriate partition between the space occupied by accelerating cores which leads to a minimum cost. While a stationary minimum exists in principle, there are cases at the low- β end of the accelerator where the stationary point is not accessible in practice -- usually because of the need to restrict the quadrupole pole-tip field to a manageable value ($\leq 4T$).

In December 1977, a first Reference Conceptual Design, called IL 4/26, was described for a 1 MJ, 156 TW driver using U^{+4} ions accelerated to 26 GeV (i.e., $V_f = 6.5$ GV).⁽²⁾ While we were aware at that time of the general design criteria described above, the detailed cost data required for evaluating cost-minima were not yet in hand then and the choices of induction-core and magnet configurations at various points along the accelerator were simply a matter of educated guessing. A block-diagram showing some of the parameters in that design is given in Figure 2. The injector (which included the stripping section) provided $[I\tau] = 155 \mu C$ and was based upon three stages of pulsed drift-tube acceleration⁽³⁾ with solenoid focussing. An appropriate bunching section was designed for the latter part of the accelerator after which the beam was allowed to become large transversely and split with a four-way septum magnet to enter the final four transport lines leading to the target chamber.

The points to be emphasized here that influence the interpretation of the partially-complete results that follow are:

- In Reference Design IL 4/26 the injector cost was about 10% of the accelerator system, and the final beam transport also represented about 10% of the cost.
- Because 80% of the cost was identified (for that case) to reside in the induction linac part from the injection voltage (50 MV) to the final voltage, $V_f = 6.5$ GeV, we decided to concentrate our efforts on refining the design procedure for this major-cost part of the system, and these are the results that are discussed below.
- We believe that the costs of the final transport and focussing systems for most of the parameter ranges to be discussed will indeed be of the order of 10% of the overall system cost, or possibly less.
- We are uncomfortable at this time about stating the scaling law for the injector cost as a function of the beam-charge $[I\tau]$ delivered. It is certainly less than linear with total charge, since at worst several injectors may always be paralleled in a tree configuration. Undoubtedly the injector cost will increase with increasing $[I\tau]$ while the induction linac cost will decrease (see below) for reasonable assumptions about the beam emittance. Thus the "10% injector-cost" rule will be violated if we wish to scale too far away from Reference Design IL 4/26, and as yet we cannot furnish a reliable estimate of by how much. The high current injector design presents a fascinating design question, and there is room and need for innovation. Several interesting ideas need pursuing, but up to this date - apart from examining some designs in the spirit of existence proofs - we have felt it more important first to address in a proper way the cost-dominating section of the system.
- Results for costs for the induction linac section given below can be referred to as "80% of cost" values but with the caveat that if one strays too far from the IL 4/26 case of $[I\tau] = 155 \mu\text{C}$, the 80% figure becomes unreliable. We feel now that a preferred reference example would be IL 4/19 with $[I\tau] = 210 \mu\text{C}$ and that more study of the injector is needed before cases with much larger $[I\tau]$ values can be reliably costed.⁽⁴⁾

3.2 Cost Procedure

Up to this point we have simplified the problem in studying the "80% - cost figure" by assuming

- (i) A suitable injector at $V_{inj} = 50$ MV is available (this has been established in detail only for the Reference Design IL 4/26).
- (ii) The final rapid-buncher section costs about the same as if it were composed of a pure accelerating section with modest bunching. (In Reference Design IL 4/26 the cost differential was small).

More work is needed on both of these topics before they can be incorporated in detail into a comprehensive cost-estimating program.

To address the main part of the Induction Linac system, viz. the "80% part", a computer program (LIACEP) has been developed to sort through the possible engineering options at each voltage point, V , along the machine and to generate the desired cost and design information.

We start by specifying an ion species with atomic weight, A , and charge state, q , (so far only Uranium with charge states 1, 2, and 4, and Cs with charge state 1, have been studied). Next, an electrical beam charge $[I\tau]$ is specified with a sequence to be explored -- 30 μC , 60 μC , 90 μC ..., etc., ... up to 1000 μC . Then at any voltage point, V , along the accelerator the cost consequences of adding a further 1 MV are examined. The independent variable is chosen to be the current, I , with the magnet occupancy factor, η , for a symmetrical FODO lattice, as a separately set and varied parameter (e.g., $\eta = .5, .33, .17, .10, .05$, etc.). In this way a set of curves for each value of η can be generated to display differential cost versus current and so to arrive at a minimum or indicate the cost/benefit ratio of departing from the minimum (see Fig. 1).

At this point we have to identify three distinct classes of information which are key ingredients of the optimization process:

- (1) Engineering Design Options and Constraints
- (2) Cost data base which can affect the trade-off among design choices
- (3) Physics assumptions about (i) the desirable beam emittance determined by the pellet and transport requirements, or the realizable beam emittance set by the source performance, and; (ii) the transverse space charge limiting current.

These input classes are discussed in sequence below. At this time the greatest cost uncertainties seem to arise from the consequences of the physics assumptions.

(1) Essential to this costing routine is the spectrum of engineering options that are examined in the process. To date we have chosen to input the engineering possibilities and constraints listed below. A few of the options, identified by the asterisk, have not yet been exercised in the program (which is still under development):

- A: Accelerating module design based upon an economic choice between iron or ferrite
- A: Accelerating module design based upon an economic choice between amorphous ferromagnetics or ferrite⁽⁵⁾
- B: A module design with the oil-vacuum interface insulator near the inner radius of the cores (Fig. 3)
- B: A module design with the insulator near the outer radius of the cores (Fig. 4)
- B: A module design wherein the transport magnets can be re-entrant within the pulsed cores (most appropriate for low- β section)

- * B: A module design with radial sub-division of the cores⁽⁶⁾
- * C: Conventional-conductor/iron quadrupole transport magnets (appropriate for test facility but probably not for power-plant)
- C: Superconducting quadrupole magnets
- D: Constraint that the quadrupole "pole-tip" field does not exceed 4T
- D: Constraint that the quadrupole bore-radius to length ratio never exceeds 0.25.
- D: Constraint that the electrical stress on the insulator never exceeds 10 kV per cm for pulse duration greater than 1 μ sec and 10-40 kV per cm for pulse durations of less than 1 μ sec.
- D: Constraint that the "longitudinal space-charge factor" (LSCF) never exceeds 0.1. The LSCF is defined as the ratio of the extra gradient needed to hold together the ends of a beam bunch with 10% tapered ends to the average accelerating gradient. This constraint implies at most an extra 1-2% of overall core volt-seconds in the accelerator if separate longitudinal focussing modules are used.
- D: Constraints on the maximum "reasonable" radius of a core and on the maximum weight of an assembled module.
- D: Constraint that the maximum beam-pipe bore radius not exceed 0.2 m.

(2) The cost input data are of such complexity that they cannot be discussed in detail in this report. Briefly, their breakdown falls under the following headings:

A. Technical Components

1. Accelerating Modules (cores, insulators, structures, etc.)
2. Pulsers
3. Vacuum System
4. Support and Alignment
5. Control Room
6. Computer System
7. Beam monitoring and control
8. Quadrupoles, refrigeration and cryogenic distribution, power supplies, testing, control, support and alignment.

B. Conventional Facilities

1. Site Work
2. Accelerator Housing
3. Control Room Building

4. Mechanical Facilities
5. Electrical Facilities
6. Safety

Details of the unit costs based upon manufacturers' quotes, and the interpolation or extrapolation formulas based upon projects completed or under construction are documented in internal LBL engineering notes by E. Hoyer. An obvious advantage of having the program, LIACEP, to sort through many cases is that by varying the input cost data we can quickly identify those items or design features to which the overall costs are most sensitive.

(3) Until adequate experiments can be carried out for high current heavy-ion beams on achievable beam brightness and on the details of the transverse space-charge limit we shall continue to have uncertainties in specifying these quantities precisely. These uncertainties span actually a rather narrow range but unfortunately can lead to significant cost effects. The first of these arises from the fact that in the final focussing lens the third-order geometric aberrations impose a condition that the entering beam (or beamlet) have an upper limit on emittance. From the work of Garren⁽⁸⁾ and Neuffer⁽⁹⁾ we have derived the following approximate expression for this emittance limit in a single plane (x, for example):

$$\epsilon_N^L \lesssim 0.12 \beta_Y r_s^{4/3} \quad (3)$$

where the superscript, L, refers to the doublet lens, the subscript, N, indicates normalized emittance, and r_s is the target spot radius. If we denote by ϵ_N^T the total normalized emittance of the beam transported through

the accelerator then the number of final separate beamlets, N_b , required to meet the target needs can be expressed as

$$N_b \geq \frac{(\epsilon_N^T)_{\text{HORIZ}} (\epsilon_N^T)_{\text{VERT}}}{(\epsilon_N^L)_{\text{HORIZ}} (\epsilon_N^L)_{\text{VERT}}} = \frac{2}{3} \left(\frac{\epsilon_N^T}{\epsilon_N^L} \right)^2 \quad (4)$$

where the factor 2/3 arises from the fact that in the y-plane the emittance can be some 50% larger than the x-plane emittance limit given by Eqn. (3); this comes about because of the inherent x-y asymmetry of a doublet lens.

An example of a four-beamlet splitter using current-sheet septum splitting magnets and quadrupoles is shown in Fig. 5. This represents one half of an "eight-beamlet" system for pellet irradiation, i.e., two clusters of four beamlets from opposite directions. When one examines the engineering details of arranging for a large number of beamlets in a cluster then it appears that the complexity becomes formidable for N_b much in excess of 20.

These considerations thus impose a constraint on the total beam emittance, ϵ_N^T , that can be tolerated in the accelerator and this probably should not exceed 3×10^{-5} rad-m. for the reference 1 MJ design. The studies show that the capital cost decreases and the electrical efficiency increases if a higher value of emittance can be tolerated; this comes about because the space charge

limited current is proportional to $(\epsilon_N^T)^{2/3}$. This sensitivity of cost and efficiency to the space-charge limited current seems a general feature and it becomes important to have a good understanding of what betatron tune depression can be safely tolerated in the transport system. Extensive studies of this question have been carried out by Laslett using computational techniques for a Kapchinskij-Vladimirskij distribution⁽¹¹⁾ and by Haber using numerical simulation codes.⁽¹²⁾ Conclusions have varied somewhat from time to time and a convincing final result is not yet available. Early LIACEP program runs used a tune depression $\sigma_0 \rightarrow \sigma$ of $90^\circ \rightarrow 36^\circ$, later this was revised to $90^\circ \rightarrow 57.5^\circ$ and still later to $60^\circ \rightarrow 24^\circ$. The non K-V case results by Haber⁽¹³⁾ suggest that a tune depression $90^\circ \rightarrow 30^\circ$ may perhaps be tolerable, but no cost study has been made for this case. Such uncertainties in the tune-depression specification are reflected in cost uncertainties of as much as 20%.

The LIACEP program procedure for a particular choice of tune-depression is to pre-set the magnet occupancy factor, η , and calculate magnet length, period length, and magnet pole tip field for a variety of beam currents, and later to cycle through several values of η . Thus in any instance the magnet parameters and the available space for the accelerating modules is derived and the appropriate engineering solutions described earlier can be examined.

3.3 Results

It must be emphasized that these "80% cost" studies are useful as a design guide and as a tool for identifying the cost sensitivity to any of the input assumptions and engineering options and costs. Thus the absolute value of the cost figures should be treated with considerable caution and attention focussed on the trends suggested by the data; in our view, reliable costs can be derived only when a particular case is settled upon and an *ab initio* design carried through in detail for that case. The sample results given here reflect work-in-progress, and inconsistencies in assumptions will be noticed. Fig. 6 shows example results for minimum "80%-cost" designs as a function of charge-state for uranium and an example point for Cs^{+1} . The interesting result is that the variation is not large but higher charge states are favored on cost grounds by perhaps 25%. There are physics arguments favoring the lower charge states which correspond to lower kinetic-energy (shorter range) examples.

These examples used a tune depression $90^\circ \rightarrow 57.5^\circ$ and an emittance $\epsilon_N^T = 2 \times 10^{-5}$ rad-m.

Fig. 7 shows costs for U^{+4} (again for the same tune-shift) if the emittance can be permitted to be as high as 4×10^{-5} rad-m, and constant at that value independent of the beam charge $[I_T]$. The minimum for most energies seems broad and in the range $[I_T] = 200 - 500 \mu\text{C}$.

Fig. 8 shows costs for U^{+4} with different assumptions for tune-shift ($60^\circ \rightarrow 24^\circ$) and emittance. The normalized emittance is assumed to be 3×10^{-5} rad m up to $[I_T] = 210 \mu\text{C}$ and to scale as $[I_T]^{1/2}$ beyond that point. If the increased beam charge is achieved by increasing the area of the ion source then this square-root law would arise naturally. The increase of emittance for higher beam charge does not lead to difficulties in the final focus since the target spot radius can also be larger. Note that the curves for fixed joules tend monotonically downward towards higher beam charge; this

arises primarily from the corresponding allowed increase in emittance. It must be emphasized again, however, that the cost of the injector will increase as $[I\tau]$ increases and the overall cost of the accelerator may show a stationary minimum.

Fig. 9 summarizes information for the new reference design IL4/19. Illustrated are the theoretical maximum current variation as a function of voltage along the accelerator (close-packed magnets, and tune-shift $60^\circ \rightarrow 24^\circ$), the practical maximum current set by the structure constraints discussed earlier, and the way the current would vary for an accelerator that used the minimum-cost solution at each point. Also shown are the ranges of beam-current variation allowed for costs up to 20% above minimum. The higher the current the higher will be the electrical efficiency so if the latter were to be a prime consideration for the 1 MJ driver it could pay to choose to increase the capital cost of the last part of the accelerator by some 20%.

TABLE I

Example Parameter Choices for a 1 MJ U^{+4} Driver

$[I\tau]$ μC	T GeV	V GV	R g/cm^2	R_T mm	ϵ_N^T ($\times 10^5$) rad-m	ϵ_N^T ($\times 10^5$) rad-m	N_B >
150	26.7	6.67	.78	1.01	.77	3	10
210	19.0	4.76	.5	1.26	.69	3	12
300	13.3	3.33	.33	1.55	.79	3.6	14
500	8.0	2.0	.17	2.16	.935	4.6	16
1000	4.0	1.0	.08	3.15	1.07	6.6	25

Table I shows a variety of parameter options for a 1 MJ driver. The first entry is close to the old Reference Case IL4/26 and the second entry corresponds to the new Reference Case IL4/19. The succeeding entries have advantages in allowing large pellet radii but realistic injector designs will have to be developed for each before they can be properly evaluated.

We wish to acknowledge the help of Mr. Victor Brady in performing much of the computational work.

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9. D. Neuffer, Geometric Aberration in Final Focusing, HI-FAN-36, (1978).
10. D. Neuffer, Unpublished, (1978).
11. L.J. Laslett, L. Smith, J. Bisognano, Computational Study of a Third-Order Instability Suggested by Computations of Dr. Haber, HI-FAN-43, (1978).
12. I. Haber and A. Maschke, Steady State Transport of High Current Beam in a Focused Channel, NRL-3787, (1978).
13. I. Haber, private communication, October, 1978.

Figure 1

EXAMPLE COST CURVE

TENTATIVE COST FIGURES FOR EXAMPLE INDUCTION LINAC

26 GeV, U^{+4} , 1MJ, 156TW (4 beams), $\epsilon_n = 2 \times 10^{-6}$ radian-meters, $B_{\text{pole tip}} = 4T$.

* U^{+1} SOURCE - HELIUM STRIPPER,
 U^{+4} PULSED DRIFT TUBE - INDUCTION LINAC INJECTOR

Figure 2

XBL 7810-12083

FERROMAGNETIC CORE MODULE - TYPE 2

Figure 3

XBL 789-10717

FERROMAGNETIC CORE MODULE - TYPE I

Figure 4

XBL 789-10716

XBL 7810-12078

Figure 5

SCHEMATIC - 1 BEAM TO 4 BEAM SPLIT AND FOCUS

XBL 7810-12079

Figure 6

MINIMUM INDUCTION ACCELERATOR COST
FROM 50MV USING METALLIC GLASS
CORES FOR URANIUM & CESIUM FOR
90° - 57.5° PHASE SHIFT, &
 $\epsilon_N = 2.0 \times 10^{-5}$ M-RAD

XBL 7810-12080

Figure 7

MINIMUM INDUCTION ACCELERATOR COST FROM 50MV USING METALLIC GLASS

U^{+4} , $90^\circ - 57.5^\circ$ PHASE SHIFT, & $E_N = 4.0 \times 10^{-5}$ M-RAD

Figure 8

MINIMUM INDUCTION ACCELERATOR COST FROM 50MV USING METALLIC GLASS

& FERRITE CORES FOR $A = 238$, $z = +4$, $60^\circ - 24^\circ$ TUNE SHIFT

XBL 7810-12082

Figure 9

ACCELERATOR CURRENT AND PULSE
DURATION FOR REFERENCE I.L.
CASE 4/19 (1MJ - 100 TW)

4. THEORETICAL ACTIVITIES

Progress this year has been achieved in three major areas:

4.1 Beam Transport (J. Bisognano, I. Hofmann, L. J. Laslett, L. Smith)

Further work on instabilities of the Kapchinskij-Vladimirskij (K.V.) distribution has led to revision of the recommended choice of maximum transportable power for design purposes. A significant achievement has been the successful comparison between our theoretical results and the simulation computations by Irving Haber for a particular unstable mode; this comparison gives credence to both the theoretical and simulation work and suggests that the simulation approach can be trusted when applied to more realistic distributions, which cannot be treated analytically.

4.2 Final Focussing (A. Garren, D. Neuffer)

The work of A. Garren⁽¹⁾ on the parametrization of a final focusing doublet has been extended to triplets, which are more suitable in certain parameter regimes. The effect of third order geometric and fringing field aberrations in the final lens system has been explored, leading to constraints on the emittance of the individual beams approaching the target. The effect of chromatic aberrations has been studied quantitatively and appears to be somewhat more serious than indicated by the previously used rule of thumb; work has begun on the correction of these aberrations by the use of bending magnets and sextupoles upstream from the final lens system.

4.3 Parameter Studies (D. Judd, L. Smith)

In light of the constraints imposed by the final focusing system, the six-dimensional phase space requirements have been re-formulated and used to develop a number of r.f. linac and synchrotron scenarios. As others have found, the synchrotron schemes do not look very attractive, particularly since the trend this year has been toward lower kinetic energy and higher current, whereas the virtue of a synchrotron is rather to provide high kinetic energy at low current.

4.4 Comparison of Instability Theory With Simulation Results (L. J. Laslett and L. Smith in collaboration with I. Haber, Naval Research Laboratory)

Introduction

For the past year and a half, a parallel effort of analytic work and simulation computations has been in progress for the purpose of understanding the nature of instabilities which arise in the transport of intense ion beams and finding safe regions of operation.¹ The two approaches have agreed qual-

itatively in that simulation runs using initial conditions predicted by the linearized theory to be highly instable indeed distinctly show instability, and subsequent saturation may occur only after an increase in emittance by a factor of two or three. Since the theory predicted pronounced instability for a large number of modes concurrently, no attempt was made at a quantitative comparison. Only recently we found a combination of parameters for which the theory predicts only one unstable but rapidly growing mode, and the corresponding simulation run shows an orderly growth in the early stages (presumably the linear regime) with the expected qualitative appearance. Since the linear theory provides definite predictions of the evolution of various moments of the distribution and the distortion of the boundaries of the various two-dimensional projections of the distribution, we undertook a quantitative comparison as a means of simultaneously establishing the validity of the theory and the reliability of the simulation procedure.

Method²

The KV distribution is the only one we have found to be amenable to theoretical analysis for a quadrupole-focussed beam³ and consequently has been used most often also in the simulation work. The case to be discussed is a FODO lattice with a phase advance of 90° per cell at zero intensity, but depressed to $\sigma \cong 45^\circ$ by the beam loading. According to the theory, a fluctuation of charge density from the unperturbed uniform density giving rise to a deviation from the quadratic electrostatic potential of the form $V = Ax^3 + Bxy^2$, or $Ay^3 + Byx^2$, should alternate in sign and grow in magnitude each period of the transport structure. The specific comparison between theoretical and simulation results that we report here for this "third-order" mode considered odd moments (such as y^3 , y^2p_y , ...) and the y, p_y projected distribution obtained for a 2048-particle sample available from the 16000-particle simulation run mentioned above. According to the theory, the boundary of the y, p_y projection should develop as described by the equation

$$\begin{aligned} \left(\frac{y}{b}\right)^2 + \left(\frac{p_y}{p_{y,\max}}\right)^2 + C \left[r_1 \left(\frac{y}{b}\right)^3 + r_2 \left(\frac{y}{b}\right)^2 \left(\frac{p_y}{p_{y,\max}}\right) + r_3 \left(\frac{y}{b}\right) \left(\frac{p_y}{p_{y,\max}}\right)^2 \right. \\ \left. + r_4 \left(\frac{p_y}{p_{y,\max}}\right)^3 + t_1 \left(\frac{y}{b}\right) + t_2 \left(\frac{p_y}{p_{y,\max}}\right) \right] = 1, \end{aligned} \quad (1)$$

where C should grow, as the instability develops from the noise, in direct proportion to λ^P -- λ being the theoretical eigenvalue of the unstable mode ($|\lambda| > 1$) and P the period number. The coefficients $r_1, r_2, \dots, t_2$, however, are uniquely given by the theory, once the tunes σ_0 and σ are specified, as values that are rather insensitive to the fractional amount by which the lengths of the quadrupole lenses occupy the transport lattice. The growing y -moments, moreover, similarly are expected to bear a definite ratio to one another and to the factor C in Eq. (1), so that in principle only one adjustable parameter is available for fitting simulation results of the type mentioned.

Results²

For purposes of the comparison, theoretical coefficients were evaluated for a 90-degree lattice, one-sixth occupied by quadrupole lenses, in which (as estimated from trajectories of the simulation particles) the space-charge forces depressed the tune to $\sigma = 45.85$ degrees (near the expected center of the predicted strong third-order instability). The theoretical value of λ under these circumstances is $\lambda = -1.2676$ (real, but negative)⁴, and the expected ratios (normalized so that $\langle y^3 \rangle = 1$) are as shown by the first line of entries on Table I.

The growth of moments obtained from the simulation data was examined only beginning with period number 8 or 9 (where the results began to emerge somewhat consistently from the noise) through period 19 or 20 (at which point some indication of incipient saturation became apparent). Taking into account the possible presence of some constant background noise in these moments, we estimated their growth as characterized by λ values in the range between -1.22 and -1.28 (average value for the six moments examined = -1.26, in good agreement with the theoretical value) and obtained the moment ratios shown by the second line of entries in Table I.

The coefficient C in Eq. (1) for the y, p_y projection was adjusted for a best fit of the simulation data only for periods 8, 13, and 18. The values so obtained suggested a growth rate characterized by $\lambda \approx -1.2$ -- i.e., somewhat less than estimated from the growth of the moments. To relate the magnitude and sign of C to values found for the moments at period 18, the observed moment $\langle p_y^3 \rangle$ reduced to "scaled variables"⁵ is approximately $+4.07 \times 10^{-3}$ and the corresponding expected value of the dimensionless parameter C is close to this value, while the best fit to the boundary of the y, p_y projection

TABLE I

Normalized Moments

	$\langle y^3 \rangle$	$\langle y^2 p_y \rangle$	$\langle y p_y^2 \rangle$	$\langle p_y^3 \rangle$	$\langle y^5 \rangle$	$\langle p_y^5 \rangle$
Theoretical	1.	1.35	-0.665	-0.94	111.	-66.
Simulation	1.	1.23	-0.63	-1.08	111.	-67.

at period 18 gave the similar value 3.84×10^{-3} . Although it is our expectation to examine the simulation data in further detail, the evidence cited above indicates that the theory for the third-order perturbation modes of a Kapchinskij-Vladimirskij distribution provides a good account of the initial instability exhibited by simulation computations for a similar initial distribution.

Conclusion

Numerical calculations based on the theory just mentioned suggest that, with a zero-intensity tune $\sigma_0 = 90$ deg., stability cannot be assured for beam intensities that depress the tune to below $\sigma \cong 57.5$ degrees. It is found, however, that this limitation is relieved by designing the transfer lattice so that $\sigma_0 \leq 60$ deg., because third-order instabilities then are not to be expected. Accordingly, with $\sigma_0 \leq 60$ deg., intensity limitations would be imposed only through the action of other, higher-order instabilities. Specifically, with $\sigma_0 = 60$ deg., intensities that result in a tune depression to σ in the neighborhood of 24 or 28.2 deg. (where substantial instabilities of 6th or higher order may appear) may be permissible and permit the transport of significantly greater currents than would be possible with a lattice designed for $\sigma_0 = 90$ degrees. The use of a transport lattice designed for $\sigma_0 = 60$ deg., and a comparison of its characteristics with those of a lattice with $\sigma_0 = 90$ deg., will be discussed in detail (with tables) in a LBL report now in preparation ["Concerning an A-G Transport System with $\sigma_0 = 60$ Degrees", LBL Report HI-FAN-56 (1978)]. Simulation runs will be made to determine whether or not the 60° - 24° range is indeed free of unstable regions.

Acknowledgements

For assistance in the work summarized in the present note we express our thanks to our colleagues J. Bisognano, V.O. Brady, and S. Chattopadhyay of the U.C. Lawrence Berkeley Laboratory.

References

1. See Laslett, p. 112 and Haber and Maschke, p. 122 and references in those articles, BNL workshop.
2. This work is described in greater detail in HI-FAN-43.
3. See HI-FAN-13, 14, and 15.
4. The distinctive signature of this instability (associated with a negative real eigenvalue) is that the odd moments (of order 3, or greater) and the boundary in phase space (or of any projected distribution) oscillates with a "frequency" of one half period of the transport lattice and with growing amplitude, but the particles distribute themselves within the boundary so that their centroid remains stationary.
5. G. Lambertson, L.J. Laslett, and L. Smith, "Transport of Intense Ion Beams", IEEE Trans. NS-24, 993 (1977).

5. TOPICAL WORKSHOP

Focussing of Beams Onto the Target of a Heavy Ion Fusion Reactor:

Summary of a meeting held at
Lawrence Berkeley Laboratory

August 7-8, 1978

A. A. Garren

1. An informal meeting was held to exchange information on work that has been done and to identify the areas most in need of investigation.
 2. The main participants were the following:
 - ANL: R. Arnold, S. Fenster, E. Colton
 - BNL: A. Maschke
 - LBL: M. Donald, K. Halbach, A. Garren, L. Smith, D. Neuffer, D. Judd, G. Lambertson

 - SLAC: K. Brown, W. Herrmannsfeldt
3. Relevant work has been done on the following topics:
 - Beam line design for Hearthfire III - E. Colton, S. Fenster
 - Beam line design from an induction linac - A. Garren, D. Neuffer
 - Preliminary study of the magnitude of aberrations from the final lenses - D. Neuffer
 - Procedures to correct chromatic aberrations without producing large geometric aberrations, using sextupoles - K. Brown
 - Ways to produce achromatic beam spots with quadrupoles only - K. Halbach
 - Dimensionless scaling of parameters for the final doublet - A. Garren
 4. Summarizing the work to date, beam lines for final focussing with beam and target parameters currently under consideration are probably feasible from the standpoint of linear optics, but non-linear and space charge effects require more study.

5. Therefore, further or new work is especially needed on
 - a) Correction of second order aberrations in currently designed beam line with sextupoles.
 - b) Evaluation of third and higher order aberrations in these lines.
 - c) Calculations on quadrupole and sextupole settings of the beam-line taking account of space charge.
 - d) Allowance for the fact that space charge will vary with position along the bunch and with path length, if the bunch is imploding longitudinally.
 - e) Estimates of tolerances.
 - f) Extension of scaling curves to take account of aberrations.
 6. As information of the above topics is developed, it should be possible to determine if the presently proposed target-beam parameters are realistic from the standpoint of the final focussing, and, if not, in what ways they should be adjusted.
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6. HEAVY ION FUSION NOTES [From April 1—Sept. 30]

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HI-FAN-34	A. Faltens	Linear Induction Accelerator Core Materials	5/8/78
HI-FAN-35	I. Hofmann	On a Class of Instabilities Which Have Been of Concern in Beam Transport for Heavy Ion Fusion	5/1978
HI-FAN-36	D. Neuffer	Geometric Aberrations in Final Focusing in HIDE	5/78
HI-FAN-37	L.J. Laslett	Notes Concerning 3rd-Order Modes for $p = 4$ and $\sigma_0 = 120$ deg. or 125 deg.	6/14/78
HI-FAN-38	L. J. Laslett	Letter to Dr. Irving Haber-dated 6/30/78	6/30/78
HI-FAN-39	L.J. Laslett	Letter to Dr. Irving Haber-dated 7/10/78	7/10/78
HI-FAN-40	L. J. Laslett	Letter to Dr. Irving Haber-dated 7/11/78	7/11/78
HI-FAN-41	D. Neuffer	Insertion of Skew Quadrupoles to Exchange $x - x'$ and $y - y'$ Phase Spaces	August 1978
HI-FAN-42	A. Garren	Focussing of Beams Onto the Target of a Heavy Ion Fusion Reactor: Summary of a Meeting held at LBL Aug. 7-8, 1978	August 1978
HI-FAN-43	J. Bisognano L. J. Laslett L. Smith	Computational Study of a Third-Order Instability Suggested by Simulation Computations of Dr. Haber	Sept. 1978
HI-FAN-44	J. Bisognano L. J. Laslett L. Smith	Third-Order-Mode Performance for an Interrupted Solenoid Transport System	Sept. 1978
HI-FAN-45	D. Judd	Phase Space Constraints on Heavy Ion Inertial Fusion Igniters and Example Design of 1 MJ RF Linac System	Sept. 1978
HI-FAN-46	D. Neuffer	Transport of a High Intensity 2 MeV Cs^+ Beam	September 1978
HI-FAN-47	L. J. Laslett	Tables Sent to I. Haber, S. Penner, M. Reiser, S. Fenster.	Sept. 1978

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HI-FAN-58	HIF Staff	Linear Induction Accelerator Conceptual Design	9/6/78
HI-FAN-59	L.J. Laslett	Letter to Dr. Ingo Hofmann - dated 10/25/78	10/25/78
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