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HEAVY ION BEAMS FOR INERTIAL FUSION*

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ABSTRACT

The United States' program in inertial confinement fusion (ICF) is described in this paper, with emphasis on the studies of the use of intense high energy beams of heavy ions to provide the power and energy needed to initiate thermonuclear burn. Preliminary calculations of the transport of intense ion beams in an electrostatic quadrupole focussing structure are discussed. In a companion paper in this proceedings, R. A. Jameson describes recent developments in low velocity accelerators for heavy ion fusion.

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INTRODUCTION

Intense beams of heavy ions can be used to convey the energy needed to compress and heat small pellets containing deuterium-tritium fuel. If the compressed fuel is confined long enough at sufficiently high density and temperature by the inertia of the pellet itself, it is believed possible to achieve pellet gains in the range of 100 or more. (Pellet gain is defined as the ratio of fusion energy yield to the energy incident on the pellet.) Such high gains require the initiation of a propagating burn in which relatively cold, high density fusion fuel surrounding the centrally ignited fuel is ignited by the energy released by the first ignition. This main body of fuel must be compressed to high densities without excessive heating.

The term Inertial Confinement Fusion (ICF) is given to the above process and the device which delivers the pulse of energy to the pellet is generically known as the driver. At present, two classes of drivers seem to have the potential of igniting pellets: high power lasers and focussed beams of ions. In the former category are solid state lasers such as neodymium glass operating at 1 micrometer; gas lasers operating a longer wavelengths such as CO_2 (10 micrometers) and HF (3 micrometers) and several short wavelength lasers operating at fractions of a micrometer. Among the ion methods two candidates stand out:

multiple beams of protons or other light ions generated in the diodes of high voltage pulsed power switching systems; and beams of heavy ions produced by high energy accelerators.

Unprecedented amounts of pulse energy and power density are required from the driver. Recent estimates for a pellet gain of 100 range from 2 to 4 megajoules energy together with a peak power of the order of 100 terawatts on a pellet having a radius of a few millimeters (Nuckolls (1979)). These estimates with suitable uncertainty hold for both laser and ion drivers. Thus, large facilities are required to demonstrate the highly nonlinear pellet scaling performance. The energies of the three major U.S. planned ICF facilities are as follows: the NOVA glass laser at the Lawrence Livermore National Laboratory, 100-300 kilojoules; the CO_2 laser, ANTARES, at the Los Alamos National Scientific Laboratory, 40 kilojoules; and the Particle Beam Fusion Accelerator, PBFA II, at the Sandia National Laboratory, Albuquerque, 3 megajoules.

The above facilities are expected to begin operation during the years 1983-1985 and should provide more definitive information on laser coupling, wavelength scaling, ablative compression, pellet stability and the ignition process. In the case of PBFA II, if plasma channelling and overlap of multiple ion beams on the pellet is reasonably successful, then the major goal of breakeven or even net energy gain (pellet output/capacitor stored energy) may be realized. (Yonas (1979))

HEAVY ION FUSION

The heavy ion method is a relative newcomer on the ICF driver scene. Following suggestions by Maschke and by Martin and Arnold, an exploratory workshop was held in 1976. (Judd *et al* (1976)) Funding began in 1977 with accelerator programs established at the Argonne, Brookhaven and Lawrence Berkeley National Laboratories. These programs were coupled to smaller programs in pellet design, reactor design, and beam transport in vacuum and gases at the Lawrence Livermore National Laboratory, the Los Alamos National Scientific Laboratory, the Naval Research Laboratory and the University of Maryland. A two-week workshop has been held each year since 1976, (Arnold (1979) and Smith (1978)) the most recent emphasizing detailed accelerator issues such as beam stability at high currents (Herrmannsfeldt *et al* (1980)). Recently the Los Alamos National Scientific Laboratory has been designated as the lead laboratory for Heavy Ion program technical direction.

The heavy ion option is an important alternative to laser and light ion drivers for a combination of reasons, as follows:

- The range-energy relations for the stopping of energetic heavy ions are well known and are believed to be completely classical, even in the hot plasma of the imploding target wall.

- Building on decades of high energy accelerator development, the studies to date indicate that the required intensities of heavy ions can be generated and focussed onto a pellet from a range sufficient to protect the focussing elements and the walls of a reactor chamber.

- Particle accelerators scale favorably to the high (multi-megajoule) energies now believed to be required for pellet gain. That is, the ability to focus the beams improves and the cost per megajoule is reduced as the required energy increases.

- High energy linear accelerators have good inherent electrical efficiency and already developed repetition rate capability.

Accelerator designs were narrowed in 1978 to two quite different approaches: a conventional rf linac with a system of storage rings for current multiplication; and a single-pass-induction linac propelling one bunch of ions using waveform shaping to compress the bunch and increase the current during acceleration. Both methods require some induction cavities for final stages of bunch compression.

Beam requirements representing a compromise between pellet design and accelerator design have evolved to the point where a set of parameters has been adopted for purposes of additional studies and for system comparisons. These parameters are, for a high gain pellet:

Kinetic energy	10 GeV
Total pulse energy	3 MJ

Peak power	150 TW
Pulse length (at peak)	16 ns
Pulse length (total)	40 ns
Radius on pellet	2.5 mm

Ions at or above atomic mass 200 are assumed. The number of final beams is left to be determined by design. Comparison with previous workshops shows that the kinetic energy has decreased and the pulse length and radius have each increased by a factor of about two. Considerations of space charge forces, particularly in final beam transport, indicate that a low ion charge state, probably one or two, will be required for a reasonable number of beams.

RF LINAC

Accepted rf designs employ relatively conventional Wideroe and Alvarez linacs extrapolated to their empirical and/or calculated beam current limits. The basic design problem is to achieve the maximum beam current allowed at each stage of the acceleration for the required phase space volume. Since allowed current increases rapidly with kinetic energy, a system of "funneling" has been proposed to build up the current. In this system a downstream linac operating at frequency Nf is filled from N upstream linacs of frequency f in binary sequence. Fig. 3 and Table I of Jameson (1980) show an example of a funneled rf linac system.

Since at each transition to a doubled-frequency linac two beams are merged by filling alternate rf cycles, the phase space volume can in principle be conserved. In practice some emittance growth is expected and remains to be measured.

By employing the techniques just described major advances in linac beam current should be attainable. In the example chosen by Jameson (1980) the current in the final Alverez linac is an impressive 800 mA. At such currents questions of beam stability are important and may represent a limitation. The conclusion from the 1979 workshop was that, at ∿ 300 mA, transverse beam blowup is not expected and longitudinal blowup is unlikely but must be calculated. In any event, the rf linac represents a conservative, well understood method for producing energetic beams of heavy ions at high power and high electrical efficiency. Considerable room for creativity clearly exists in the engineering design features such as the funneling system to reduce the complexity of the low-beta multibeam components.

CURRENT MULTIPLICATION FOR RF LINACS

Because the maximum current that can be accelerated in an rf linac is still far less than that needed for the pellet, a system of storage rings is used to accumulate the high energy ions. The rings are filled sequentially and then the ions are extracted and transported to the pellet from all the rings simultaneously. Typically, five to ten rings are required with radii of 50-100 meters. Current multiplication is obtained from the product of the number of rings N_r, the number of turns injected from the linac into each ring N_t, and the bunch compression just prior to extraction, C. Thus, $I = I_o \cdot N_r \cdot N_t \cdot C$. Again we summarize here the most recent studies since conceptual designs and an Argonne "test bed" system are well described in the workshop proceedings. Coherent longitudinal instability may limit the beam current in the rings. Estimates at the 1979 workshop based on experience with protons indicate that the effect is tolerable for a structure coupling impedance of 25 ohms. It is also quite possible that the growth time for the instability may be longer than the millisecond accumulation time. However, both the impedance and the growth rate need more study.

In one workshop design a bunch compression by a factor seven in the ring is achieved in about sixty turns using rf fields of two to four MV per turn. This process necessarily entails crossing of ring resonances. Preliminary estimates indicate tolerable emittance growth but more detailed effort is called for.

Atomic collision losses, whether internal charge-changing or residual gas interactions, are potentially troublesome due to uncertainties in some relevant cross sections. Using estimated cross sections, a beam loss of 2% has been calculated for the 3 MJ beam case. Again, more detailed information would be desirable. In this connection the ongoing atomic measurements effort at the

University of Belfast should increase the available data base significantly. This effort and others are described in a recent workshop proceedings (Jorna (1980)).

A new potential problem highlighted at the 1979 accelerator workshop concerns small beam loss on the septum normally used to deflect an incoming beam into a ring. A cloud of gas and debris emitted from a septum could result in significant losses for the subsequent beam entering the septum region. Very preliminary estimates at the 1979 workshop indicate that the septum loss should be held to $\leq 10^{-4}/\text{cm}^2$ of septum.

INDUCTION LINAC

In this method a single high current beam from the injector and low-beta sections (e.g., ∿ 10A at ∿ 5MeV) is accelerated to final energy in a long (∿ 6km) linear induction accelerator. For best overall efficiency the peak beam current is maintained close to the transverse space charge limit throughout the accelerator (Hoffman, Laslett and Smith (1980)).

The Berkeley group has chosen the transverse focussing strength equivalent to 60° phase shift of oscillation per cell, depressed to no less that 24° per cell by space charge. The induction linac method requires a gradual compression (shortening) of the beam pulse accomplished by ramping the accelerating waveform so that the rear of the beam pulse has slightly higher velocity than the front. The large single "sausage" of charge contrasts with $\sim 10^5$ "beads" of charge in the rf linac.

The induction linac method is simpler conceptually than the rf method because there is no need for a linac funnel system and storage rings. However, because induction linacs have only been demonstrated for electrons traveling essentially at the velocity of light, there is an urgent need for experimental demonstration of this method. The most serious technical issue is the longitudinal and transverse stability of the beam against fluctuations in charge density, waveform errors, bunch end effects, and structure effects. Jameson (1980) gives a brief description of a test bed accelerator proposed by the Lawrence Berkeley Laboratory to address these questions experimentally.

INJECTORS FOR INDUCTION LINACS

Jameson (1980) describes the drift tube linac system being developed at LBL as an injector for the linear induction accelerator. To extend this concept to longer pulse length, it is proposed to add a system of periodic electrostatic focussing. One such system is described by Jameson. However, recent studies indicate that a strong focussing system using electrostatic quadrupoles may be more effective.

For the purpose of the generation and transport of intense ion beams, the definition of "low energy" might well be the energy range for which the $\vec{v} \times \vec{B}$ forces, for practical magnetic fields, are too weak to overcome the space charge forces. Within this range, electrostatic forces are more effective for focussing.

For heavy ions, at low charge states, the definition extends the range of low energy to several MeV. The versatility and broad range of experience with alternating gradient focussing systems using magnetic quadrupoles leads naturally to interest in applying these techniques to transport with electrostatic quadrupoles. There are, however, some notable differences between electric and magnetic focussing systems that require examination. These differences, in general, stem from the work done on the charged particles by the electric fields.

Stability in magnetic transport systems has been examined analytically by Hoffman, Laslett and Smith (1980) and numerically by Haber (1979) and others. By both techniques, it is found that there is a range for stable transport that can be defined by the phase advance per focussing period; for a given phase advance without space charge, there is a maximum phase shift due to space charge, to a lower phase advance, which corresponds to the maximum current which can be transported without inducing instabilities.

One example of a transport stability limit, that has been extensively studied, is the case of phase advance $\sigma_0 = 60°$, (at zero current) leading to a phase shift down to $\sigma = 24°$ at the stability limit. For the electrostatic quadrupole system, it is found (Laslett (1980)) that, for a given ion and kinetic energy, the limiting current depends only on the focussing voltage at the edge of the beam. This dependence is plotted in Fig. 1.

There are relationships between transverse emittance, period length and aperture which must be met for the beam to be matched to the transport line. In addition the packing fraction (quadrupole length/available length) must be specified.

A series of calculations are presently underway to examine the stability limits of a system using these parameters. Numerical studies using a ray tracing program (Herrmannsfeldt (1979)) are able to calculate the two dimensional transport problem within a quadrupole lens, as shown by the example in Fig. 2. The equipotential lines in the figure are observed to be distorted by the presence of the space charge. The elliptical beam cross section is outlined by the particle orbits which were started on the beam envelope. The effects of the fringe fields at the ends of each quadrupole are approximated by a step function in the particle's momentum.

Although it is too early to report the results of these calculations, it appears that all the necessary numerical tools are in hand to make these electrostatic calculations by analogy to the magnetic studies made earlier. Experimentally, the situation is the other way around; electric quadrupole systems are being tested already in the MEQALAC and RFQ systems described by Jameson (1980). Since these are rf systems, in which bunched beams and longitudinal effects play a part, they are not fully simulated in the two dimensional calculations described above. The drift tube linac being developed as an injector for the linear induction accelerator at LBL will have electrostatic quadrupole focussing added in order to extend it to longer pulses. Since it is necessary to get through the low energy range before one can test magnetic transport systems, it is not surprising that the electrostatic focussing systems are the subject of so much interest.

FINAL BEAM TRANSPORT

In order to achieve the necessary final beam intensity at the target, it is necessary for the bunches (from either the storage rings or the induction linac) to still be ballistically compressing, longitudinally, on their way through the transport line. Thus, this line must deal with a spread in momentum, and with an increasing space charge force due to the increasing current. Considerable attention was given to this question at the 1979 workshop. Little previous work is applicable. The design problem is being approached both by modification of non-space-charge designs and by starting directly with large-scale particle simulation codes including non-uniform charge distributions. It is clear that adequate designs can be formulated without space charge. One system by Brown and Peterson discussed at the 1979 workshop is capable of focussing a momentum spread of 3% onto a 4 mm target for 85% of the beam. However, the effect of space charge is expected to be substantial. The problem may be avoided by using more final beam lines but would be costly. Work by Haber (1979) and others using simulation codes has proved to be valuable for the study of beam transport in long quadrupole-focussing channels. At the 1979 workshop Haber reported that use of the code for final focus studies had been initiated. Experimentally it may be possible to model the final focus conditions using low energy beams.

Studies of final transport in the reactor are complicated by the large number of variables. Among these are pressure and species of gas, particle energy and current, momentum distribution, reactor radius and geometry, and pellet requirements. Pending more definitive ICF reactor studies, the approach in the HIF program has been to adopt the vacuum case ($p < 10^{-3}$ to 10^{-4} Torr) as the method of choice, while continuing studies of transport in gas and plasma to explore the boundaries of operating parameters. (Jorna (1980)).

One of the favored conceptual laser-driven reactor designs is the Livermore-developed lithium fall method. In this scheme thick jets of liquid lithium are used as the first wall. During the past year it has been recognized that this concept may be consistent with the use of heavy ion beams provided the temperature of the lithium is adjusted to provide the appropriate lower vapor pressure. Studies aimed at adapting the concept to heavy ions are continuing.

Recent progress in gas/plasma transport studies has been summarized by Jorna *et al* (1980). Briefly:

- More detailed calculations of the filamentation instability have been performed.

- The effect of a forward moving stream of knock-on electrons has been included in some calculations. For extreme cases the self field of these electrons can cause defocussing of the ion beam.
- The pressure "window" at ∿ 1 Torr where the two-stream instability is collision damped and before onset of filamentation tends to disappear if the pellet parameters are changed to rely on lower kinetic energy (< 5 GeV) and/or longer focal distance (10-15 m).

These results tend to strengthen the belief that the vacuum case remains the method of choice.

CONCLUSION AND ACKNOWLEDGEMENTS

Considerable overall progress has been made in heavy ion driver studies in conceptual designs and recently in the low velocity accelerator systems. Special attention is being given to the use of electrostatic quadrupole focussing in this connection. No insurmountable difficulties have been found in the designs but much work needs to be done to determine more accurately the effects of high beam intensities in the accelerators proper, in storage rings and in the final focus. The combination of attractive features of the heavy ion method, first enunciated in 1976, continue to make it a sound investment for inertial confinement fusion.

The authors are indebted to numerous colleagues in the heavy ion community for much of the information in this review.

REFERENCES

1. Arnold R C 1979 Editor Proceedings of the Heavy Ion Fusion Workshop September 1978 ANL-79-41.

2. Haber I (1979) Proceedings of the Heavy Ion Fusion Workshop September 1978 ANL-79-41

3. Herrmannsfeldt *et al* 1980 Editors Report of the Heavy Ion Accelerator Study Session November 1979 LBL (to be published).

4. Herrmannsfeldt W B 1979 Electron Trajectory Program SLAC-226 November 1979.

5. Hoffman I, Laslett L J and Smith L 1980 Stability of the K-V Distribution in Long Periodic Transport Systems, Particle Accelerators (to be published).

6. Jameson R A 1980 Recent Advances in Low-Velocity Linacs for Heavy Ion Fusion, Paper in this Proceedings (1980).

7. Jorna S, Kim Y K, Magellsen G, Rudd E, Tidman D and Yu S Editors Report of the Workshop on Atomic and Plasma Physics Requirements for Heavy Ion Fusion December 1979 ANL 80-17 to be published (1980).

8. Judd *et al* 1976 Editors ERDA Summer Study of Heavy Ions for Inertial Fusion July 1976 LBL-5543.

9. Laslett L J 1980 private communication: Calculations for electrostatic quadrupoles are made by adapting the work for magnetic transport systems using the relation electric field E = βcB (where B is the magnetic field) to transform between the two methods.

10. Nuckolls J H 1979 pg 3-1 Laser Program Annual Report 1978 UCRL-50021-78 Vol. 1.

11. Smith L W 1978 Editor Proceedings of the Heavy Ion Fusion Workshop October 1977 BNL-50769

12. Yonas G 1979 IEEE Transactions on Nuclear Science NS-26 4160.

FIGURE CAPTIONS

1. Calculated quadrupole electrode voltage required at the edge of the beam, per ampere of current, for Cs^{+1}, $\sigma_o = 60°$ and $\sigma = 24°$. A longitudinal packing fraction of 2/3 is assumed. If the electrodes are moved radially away from the beam then the potential must be increased in proportion to the square of the aperture.

2. Equipotential lines (end view) of one quadrant of an electrostatic quadrupole due to an elliptical beam cross section. Distortion of the field lines by space charge is evident. Transverse motion of particles near the beam envelope are shown by the short line segments. The calculation is for 3 MeV Cs^{+1} at 1 ampere.

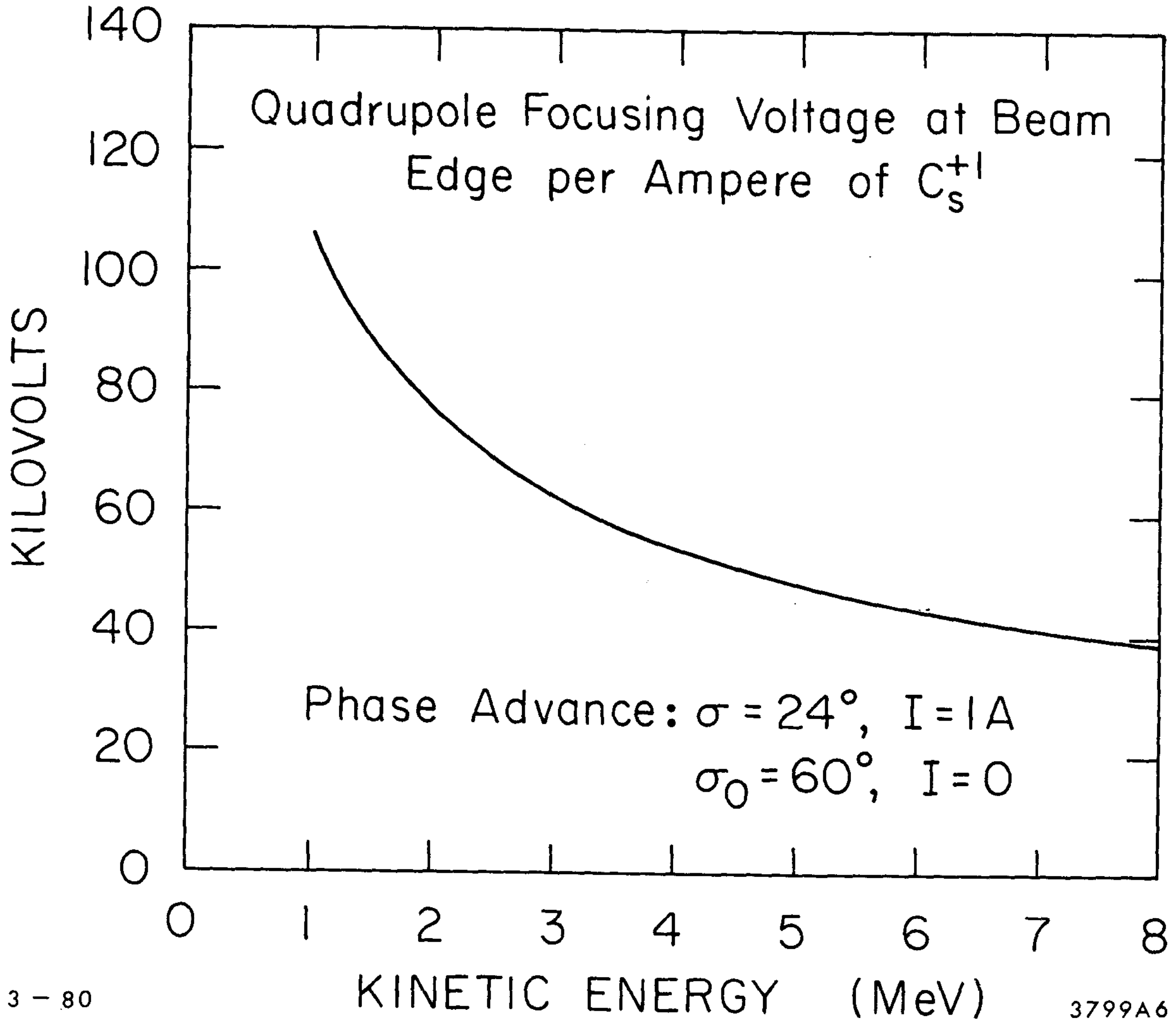
Quadrupole Focusing Voltage at Beam Edge per Ampere of C_s^{+1}
Phase Advance: $\sigma = 24°$, $I = 1A$
$\sigma_0 = 60°$, $I = 0$
KILOVOLTS
140
120
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
KINETIC ENERGY (MeV)
3 – 80
3799A6

Fig. 1

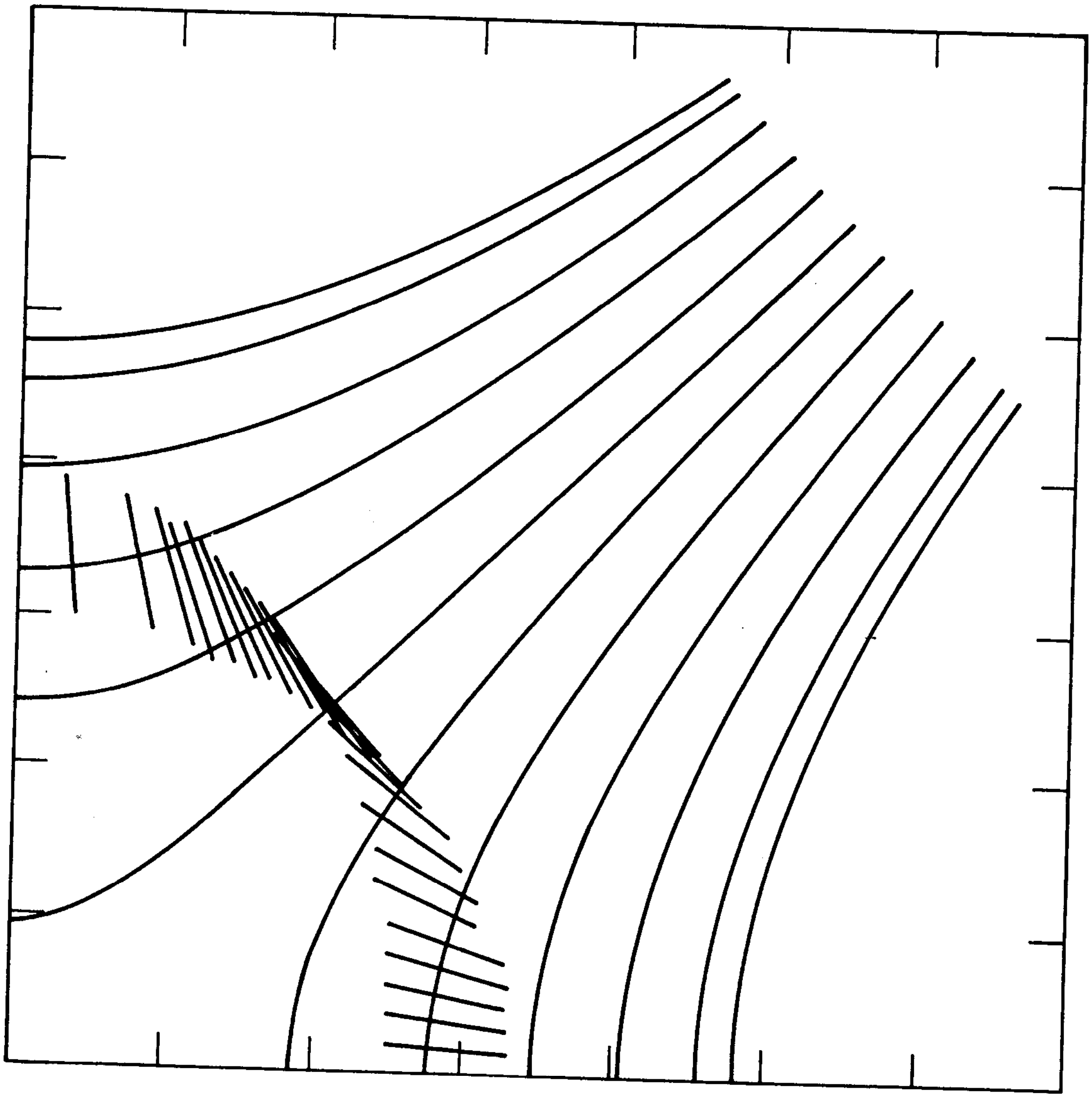

Fig. 2