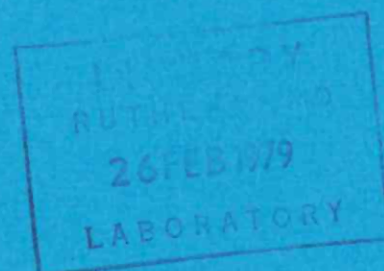


Rutherford Laboratory

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Notes of a Symposium on Heavy Ion Fusion, held at The Cosener's House, Abingdon on 16 June 1978

Edited by D E Gray

January 1979

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Notes of a Symposium on Heavy Ion Fusion, held at The Cosener's House,
Abingdon on 16 June 1978.

Edited by D E Gray

Abstract. This Symposium on Heavy Ion Fusion was held to inform the relevant University Departments and other interested organisations of the developments and prospects in this field, and to encourage them to take up problems relevant to their research fields. Three papers were presented, on 'The Heavy Ion Fusion Concept', 'Target Design for Heavy Ion Fusion', and 'Problem Areas in Heavy Ion Fusion', with open discussion after each presentation. The meeting ended with a final period of discussion, several University groups expressing their interest in pursuing some of the problems outlined.

January 1979

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A SYMPOSIUM ON HEAVY ION FUSION
HELD AT THE COSENER'S HOUSE, ABINGDON
ON 16 JUNE 1978

INTRODUCTION

The Rutherford Laboratory has been keeping a watching brief on developments in heavy ion fusion and a first report was made by the Director, Dr G H Stafford, to the Council of the SRC in December 1977. Council accepted the recommendations in the report that the Rutherford Laboratory should continue its own studies and that suitable departments in universities and polytechnics should be encouraged to take an interest in this field of research.

This symposium was aimed therefore at presenting, primarily to interested university staff, the basic concept of heavy ion fusion and the current status of its development. Problem areas were identified and suggestions made where it was thought that university departments have the expertise to play a leading role in the necessary research.

It is hoped that following discussion of these topics universities will be able to indicate the extent of their interest and that preliminary arrangements can be made for the development of the research.

List of Participants

ALLEN K	University of Oxford
ALLEN T K	AERE Culham Laboratory
ANGEL G C	Queen's University, Belfast
ARMOUR D G	University of Salford
BENNON T D	University of Birmingham
BRANDEN B H	University of Durham
CONLON T	AERE Harwell
CONSTANTINE G	AERE Harwell
DAVENPORT P A	AERE Culham Laboratory
DAVIES B	University College London
DUNN K	Queen's University, Belfast
DYER C	Royal Naval College, Greenwich
EVANS R G	Rutherford Laboratory
GIBSON J R	University of Liverpool
GRANT I	University of Manchester
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WALKER J	University of Birmingham
WILSON I H	University of Surrey

THE HEAVY ION FUSION CONCEPT

N M King

1. INTRODUCTION

"Heavy Ion Fusion" is the shorthand way of referring to the concept of thermonuclear fusion power from inertially-confined DT fuel contained in small thin-shelled target pellets and bombarded by high energy heavy ions.

During the early 1970's, studies of pellet-target compression using laser light led to consideration of other possible 'drivers', - for example, electrons, protons, light ions, - culminating in the idea of using heavy ions.⁽¹⁾ Considerable effort has been devoted to this approach during the past two years in the USA^{(2), (3)} at Laboratories including Argonne, Berkeley, Livermore and Brookhaven.

Heavy ions offer distinct advantages over all the alternative inertial confinement drivers. As far as it is understood at present, their short stopping range, mode of energy deposition in dense matter and consequent pattern of compression and thermonuclear 'burn' seem particularly efficient. Calculations carried out at Livermore predict energy gains in the range 100 - 1000 or more, depending on target design.^{(3), (4)} ('Gain' refers to the ratio of output fusion energy to input beam energy).

High energy heavy ions can be provided by accelerator systems capable of delivering large beam energies at fast repetition rates with high efficiency. Based on existing technology, typical prospective values for these quantities are: beam energies in the MJ range for ions of 20-60 GeV kinetic energy at repetition rates as high as 50 Hz or more: and efficiencies of about 25% for the acceleration system. To quote some typical examples, a pulse of 1 MJ beam energy corresponds to about 3×10^{14} caesium ions accelerated to 20 GeV, or 1.25×10^{14} uranium ions accelerated to 50 GeV: if the pulses are 10 ns long, the power in such a pulse is 100 TW. A system to give 10 MJ beam energy corresponds to about 3×10^{14} uranium ions at 20 GeV: with 50 ns pulses, the power would be 200 TW. Accelerator technology is well established and well understood, so that such parameters seem to be a reasonable extension of existing accelerator achievements. The

chief difficulty they present to the accelerator designer lies in the short pulse times required.

Constraints on reaction vessel operation may limit a given reaction vessel to accepting no more than a few pulses per second. However, the accelerator capability of fast repetition rate would allow several reactors to be driven by a single accelerator system, with consequent advantages in operation and maintenance of a fusion power plant.

Besides these attractions, heavy ions offer the important, perhaps vital, common advantage of all inertial confinement fusion schemes - a reaction vessel well-separated from the complex and sensitive driver equipment.

The specification of a heavy ion accelerator, much less a complete fusion power plant, is not of course entirely cut-and-dried. A number of problems remain to be solved, and a number of areas remain where lack of precise knowledge precludes an entirely confident scheme being proposed today. There is a wide range of problem areas in atomic/molecular physics, nuclear physics, plasma physics and reactor engineering, which John Lawson will survey in the third paper : there are problems concerned with the target physics and hydrodynamics, which Derek Beynon will discuss in the second paper : and, indeed, there are a number of unresolved accelerator problems.

These latter stem from two main sources : the simultaneous requirements of a large number of ions in the incident beam, typically in the 10^{14} range, and of a short pulse time, typically several nanoseconds. So far, the design requirements of accelerators constructed for high energy particle physics have not included such short pulses : for instance, although the 25 GeV beams of the CERN Intersecting Storage Rings have a proton flux in this range, with a beam energy of about 3 MJ, the protons are unbunched.

It is a particularly aggravating feature of the heavy ion fusion concept that attempts to design small demonstration systems lead to the requirement of shorter pulse times, - for example, about 1 ns for a 100 kJ system. Solving the resulting problem might cost more than the construction of a higher energy system in the first place. For this reason, we discuss a scheme involving 1 MJ beam energy in about 6 ns pulse time - hence on the scale of a sizeable power plant, capable of delivering several hundred MW from a single reaction vessel operated at 2 Hz. Such a scheme is illustrated schematically,

in its simplest terms, by Figure 1, - (a reproduction of a large display panel prepared for the Science Research Council's recent visit to the Rutherford Laboratory). Current US design schemes (eg Ref. 5), based as far as possible on existing technology, involve much greater complexity in the accelerator system.

Conversely, once the concept has been proven, it is an intriguing feature of heavy ion fusion that the cost per unit output energy decreases rapidly as the beam input energy is increased.

Ultimately, design decisions for a prototype heavy ion fusion scheme, whether it be an exploratory test bed or a fully-fledged demonstration power plant, involve a closely-knit reciprocal exchange of parameter specifications determined by the target geometry and by the accelerator system. The close relation between target and accelerator parameters is brought out in the following Section: starting from a particular target specification, the accelerator requirement is shown to be virtually determined.

2. TARGET AND BEAM PARAMETERS FOR A 1 MJ SYSTEM

To gain some feeling for target size in relation to beam kinetic energy and ion type, we may start from the basic formula:

$$r^2 = W/4\pi E\lambda \quad \dots (1)$$

where r is the target radius, W is the beam energy, E is the specific energy deposition, and λ is the range of the ions in the target shell material. This formula assumes uniform illumination of the target by several incoming beams. We shall also assume that beam spot radius is equal to target radius.

The beam energy W is related to the ions' kinetic energy T by the simple relation:

$$W = NeT ; e = 1.6 \times 10^{-19} \text{ coul}, N = \text{no. of ions.} \quad \dots (2)$$

Taking $W = 1 \text{ MJ}$, $E = 20 \text{ MJ/g}$, and using values for the range λ in a heavy metal target shell, equ (1) allows target radius to be plotted against kinetic energy for different types of ion. This is illustrated in Fig 2, where the λ values have been taken from Argonne data. It may be noted that, to keep N small, we have to go towards higher kinetic energy and

smaller targets for a given ion type. For the 1 MJ system, it is convenient to express equ (2) in the form:

$$N = 62.5 \times 10^{14} / T(\text{GeV}). \quad \dots (3)$$

Assuming the lowest reasonable target radius to be 1 mm, kinetic energy may be plotted against mass number, as in Fig 3. This graph is taken from Livermore data, and refers to targets with a shell of low-density material: it includes the additional information that the beam pulse time τ should be about 6 ns for the 1 MJ beam. (For comparison, the conditions for a 100 kJ system, $\tau \approx 1$ ns, are also plotted). Taking ^{133}Cs ions as an example, then $T = 20$ GeV and $N \approx 3 \times 10^{14}$ for the 1 MJ system.

The Livermore calculations indicate that about 60% of the beam power, P , should be concentrated into the quoted 6 ns, so that we have effectively:

$$P = W/\tau \approx 100 \text{ TW} . \quad \dots (4)$$

The electrical current in the beam, I_{tot} , is then given by

$$I_{\text{tot}} = zP/T = 100 z/T(\text{GeV}), \text{ for } I_{\text{tot}} \text{ in kA}, \quad \dots (5)$$

where z is the charge state of the ions. As will be remarked later, we are concerned to reduce space charge effects in the beam, so that the current should be kept small. Here we choose $z = 1$: ie, singly-charged ions.

To avoid too much complexity, we shall assume that there should be no more than 8 beams striking the target simultaneously. Taking $n_b = 8$ and $z = 1$, the current in each beam is then given by:

$$I_b \text{ (kA)} = 12.5/T(\text{GeV}) . \quad \dots (6)$$

Turning to the reaction vessel itself, we assume that the target gain, g , is 1000, so that 1000 MJ fusion energy per pulse, mainly in the form of neutrons, reaches the first wall. Assuming that the power density P_w should be no more than 2 MW/m^2 , consistent with existing reactor technology, the relation

$$P_w(\text{MW/m}^2) = 1000 f/4\pi R^2, \quad \dots (7)$$

where f is the repetition rate, and R is the reaction vessel radius, suggests the values:

$$R = 10 \text{ m}, f = 2 \text{ Hz}, P_w = 1.6 \text{ MW/m}^2 \quad \dots (8)$$

With 8 beam ports of radius A, the fraction of wall area through which neutrons will escape is given by

$$F_W = 2A^2/R^2 \quad \dots (9)$$

$$= 4.5 \times 10^{-4} \text{ for } A = 0.15 \text{ m}$$

Since the total neutron flux is of order 10^{21} , this means that we have to shield against the order of 10^{17} neutrons/sec, a sufficiently formidable problem for the final beam transport equipment.

Taking this upper limit for A, the limiting beam emittance is given by:

$$\epsilon_{\max} = rA/R = 15 \times 10^{-6} \text{ m.rad} \quad \dots (10)$$

The normalized value, using β and γ appropriate to 20 GeV Cs ions, is then:

$$\epsilon_n = 8.8 \times 10^{-6} \text{ m.rad} \quad \dots (11)$$

Similarly, a rough guide to tolerable momentum spread in the beam is afforded by relating the final focusing to a thin lens of aperture A and focal length inversely proportional to momentum p. The increase in beam spot radius at the target is then given by:

$$\Delta r \approx A \cdot \frac{\Delta p}{p} \quad \dots (12)$$

For example, with $A = 0.15\text{m}$, a momentum spread of 2×10^{-3} would increase the spot radius by 30% of its nominal 1.0 mm value.

However, we shall assume that an achromatic beam transport and focusing system may be devised to overcome this limitation, at least up to a value of 10^{-2} in $\Delta p/p$.

The above arguments have led, through a number of reasonable assumptions, from an initial target specification to a virtually complete specification of the beam to be provided by the accelerator system. Summarizing the parameters suggested above, we have:

Target Radius = Beam Spot Radius, r	1 mm
Beam Energy, W	1 MJ
Specific Energy Deposition, E	20 MJ/g
Gain	1000
Ion type, (say)	$^{133}\text{Cs}^{+1}$
Beam Kinetic Energy T	20 GeV

cont..

No of Ions, N	3×10^{14}
Pulse Time, τ (60% of beam)	6 ns
Repetition Rate, f	2 Hz
No. of beams, n_b	8
Beam Power, P	100 TW
Total Beam Current, I_{tot}	5 kA
Current per Beam, I_b	0.625 kA
Reaction Vessel Radius, R	10 m
Power density at First Wall, P_W	1.6 MW/m^2
Beam Port Radius, A	0.15 m
Max. Normalized Beam Emittance ϵ	$8.8 \times 10^{-6} \text{ m.rad}$
Max. Momentum Spread $\Delta p/p$	$2 - 10 \times 10^{-3}$, (say)

3. SPACE CHARGE LIMITATIONS

In the above argument, singly-charged ions were chosen in order to minimize the effects of space charge forces in the beam. To underline this point, two important formulae may be quoted, the first referring to a maximum power limit in beam transport lines using periodic quadrupole focusing:⁽²⁾

$$W_b \leq 1700 (\gamma-1)(\beta\gamma)^{5/3} \epsilon_n^{2/3} B_Q^{2/3} (A/Z)^{4/3}, \quad \dots (13)$$

where W_b is in TW.

The second formula refers to the tune shift in circular machines caused by space charge defocusing:

$$\Delta\nu = (r_p/ec)(Z/A)\hat{I}(R_A/\epsilon_n)(\beta\gamma)^{-2} \leq 0.25 \quad \dots (14)$$

Here,

β, γ are the usual kinematic terms

r_p = classical proton radius = $1.5347 \times 10^{-18} \text{ m}$

R_A = radius of ring accelerator, (m)

$\hat{I}$ = peak electrical current in each ion bunch, (amp)

ϵ_n = normalized emittance, (m)

Z = charge state of ions

B_Q = field on pole of focusing quadrupoles, (T)

Thus, the limitations are very dependent on ion charge state Z. Fig 4 shows

how the tune shift formula (with $Z = 1$) limits the injection and final energies for systems where the final part of the acceleration process is carried out in a synchrotron. The beam transport limitation is seen to be a lesser constraint in this case. In particular, Fig 4 suggests that ions of mass less than about 120 are not suitable for this kind of system.

4. VARIATION OF RING PARAMETERS WITH MASS NUMBER

Pursuing the comparison of different ion types suggested by Fig 4, the diagram of Fig 5 indicates how some important ring parameters vary with A .

As the mass number increases, the main advantages are that fewer ions are required, and (as seen from Fig 4) they may be injected into the synchrotron at lower energy. The particular scheme outlined here is based on the proposition that, if it proves possible to use a synchrotron rather than invoking linear acceleration throughout, the resulting system will be considerably cheaper. It should be remarked that this assumption has not yet been clearly established. In particular, linear acceleration to a given final energy and final current may become much cheaper for higher charge states, to the extent that the extra problems presented by synchrotrons may make them unattractive.

The other parameters plotted in Fig 5, - ring radius, revolution time, RF frequency, and final bunching factor, all tend to favour lower mass numbers. It was for this reason that ^{133}Cs was chosen above. In addition caesium occurs as a single isotope in nature, and sources providing the singly-charged ion are particularly free from contamination by higher charge states. Fig 4 shows that the synchrotron injection energy for caesium ions should be at least 2 GeV.

The final bunching factor is worthy of particular remark. This is the factor by which the 8 bunches created in the synchrotron at top energy have to be compressed longitudinally in order to occupy 6 ns time extent. During this compression, the tune shift greatly exceeds the limit quoted in equ (14), extending over several integers. In theory, if this can be carried out fast enough, the resonant defocusing will not have sufficient time to build up. Some experimental work on the Brookhaven AGS suggests that this process is possible, but it has not yet been clearly established for such large bunching factors as are required here. The RF problem

involved is a serious one, particularly since the frequency is so low: $f = 790 \text{ kHz}$ for 20 GeV caesium. It may prove necessary to carry out the final bunch compression in a separate DC storage ring. Some of the problems are alleviated by invoking superconducting magnets in the ring.

A particularly important design constraint on systems involving a synchrotron stems from charge-exchange collisions between ions in the beam bunches. The cross section for this process will determine a lifetime during which the beam may be injected, stacked, accelerated, rebunched and ejected. Hence, information on charge exchange cross sections for such ions as Cs, Xe, Hg, Pb, Bi and U is of considerable interest.

5. EARLY PART OF THE ACCELERATOR SYSTEM

The early part of the system is likely to be the same for any of the alternative accelerator schemes proposed, whether they involve synchrotrons and storage rings or are mainly composed of conventional Wideroe and Alvarez linacs. Induction linacs may require a different approach.

All start from an ion source which should supply between 40 mA and 100 mA into a small phase space emittance of about $2 \times 10^{-7} \text{ m.rad}$. Such sources are nearing completion at Argonne and Berkeley. The ions are accelerated initially through a DC column to a voltage in the range 0.75 - 2.0 MV. Acceleration is then taken up by special independently-tuned RF cavities, a typical choice of frequency being 12.5 MHz. From these cavities they pass into Wideroe linac sections, later Alvarez linac sections, the frequency being increased through 25 MHz up to a final value of 100 MHz as the ion velocity reaches appropriate values.

During this early part of the acceleration, space charge defocusing is particularly serious, and it is important to learn more of the limitations this will impose. It may be necessary to start from several ion sources and develop a 'tree' of linac sections, amalgamating into a single linac only when the ions have reached sufficiently high velocity.

Supposing that, at 2 GeV injection into the synchrotron, the linac bunches contain about 1.5×10^{10} ions, and that about 200 bunches may be fed in per revolution in the ring, then about 81 revolutions are required to achieve the required 3×10^{14} ions. This requires 'stacking' in both of the

transverse phase planes, (9 horizontal x 9 vertical), a process which is understood theoretically, but has so far been demonstrated only in a single phase plane. If it proves impossible to stack in both planes, then one solution would be to invoke several synchrotrons.

The filling time for the above process is of order 1 ms: acceleration time at, say, 50 Hz rep.-rate is of order 10 ms: further time is required for debunching and final re-bunching into 8 separate short bunches, involving the charge-exchange and resonant beam loss effects referred to in Section 4.

6. STRATEGY FOR THE UK

It is worth debating whether we in the UK should become involved in heavy ion fusion at this stage, in view of the relatively large investment in this field already taking place in the USA.

There are several arguments to be put forward in this context, the basic one being that heavy ion fusion bids strongly to be the best contender for large-scale economic fusion power production in the early years of the 21st century, - a prospect which we would do well to consider very carefully. Secondly, it should be remarked that the US investment is perforce spread over several different approaches in various laboratories: by concentrating our efforts on a single approach, our progress need not be insignificant in comparison.

Recent US work has been directed towards specification of complete demonstration systems, based on existing technology. The resulting schemes involve a multiplicity of accelerator components, - 'trees' of linacs, stacks of synchrotrons and bunch compression rings, large numbers of beams to the target. While this may prove necessary in the long run, there are sufficient unknowns in the problem to suggest that further theoretical and experimental studies might lead to schemes of much less complexity.

One method of approach would be, not to embark on a complete system proposal ab initio, but to engage in a serial construction of ion source, DC columns, independent cavities, linac sections, and so on. As each stage is completed, ions become available to study the different problem areas experimentally, thus providing design information for the later stages.

This approach could be achieved with a relatively modest financial commitment, at least in the early years, and would postpone the heavy investment until more confident design data is available.

Our present proposal is to start tackling the various problems we are able to define today - those in the accelerator category at the Rutherford Laboratory; and the wide range of non-accelerator problems, to be outlined in the next two papers, by interested University groups.

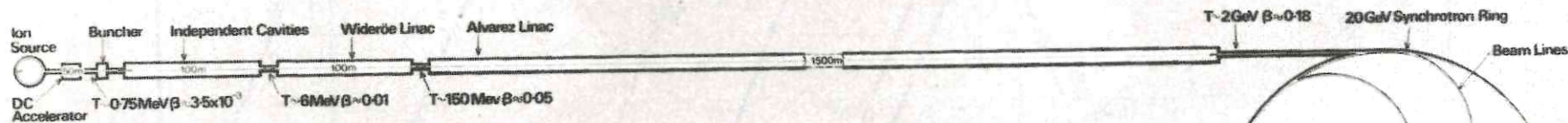
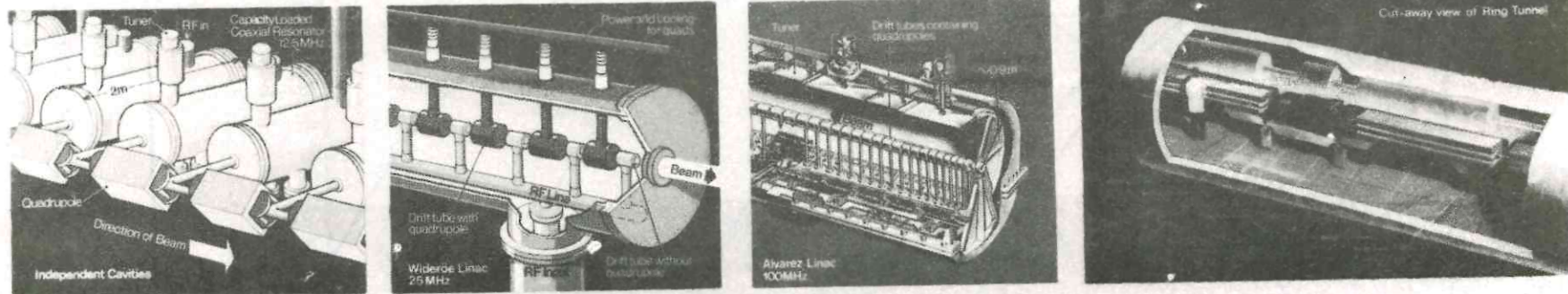
It is also worth remarking that we are contacting the interested people in Western Europe with a view to broadening interest in heavy ion fusion on a European scale. We have to bear in mind the possibility of a joint European project at some appropriate time in the future.

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Heavy Ion Fusion

a 1MJ Demonstration System giving 400MW Electrical Power



The Prospect of Thermonuclear Fusion Power from Inertially-Confined Deuterium and Tritium Bombarded by High Energy Heavy Ions.

The demonstration plant illustrated here is one of several possible approaches.

Caesium ions, ($^{133}\text{Cs}^+$), are accelerated to 20 GeV kinetic energy in a series of linear accelerators followed by a synchrotron. With about 3×10^{14} ions, the total energy in the beam is 1 MJ. The beam is concentrated into 8 separate bunches and compressed longitudinally so that each bunch occupies no more than 6 ns in time. The eight bunches are ejected simultaneously and transported to the centre of a reaction vessel, where they are focussed on to a small target pellet, several mm in diameter.

The pellet consists of a thin lead or gold outer shell, a layer of low density material, and 1 or more layers of deuterium-tritium fuel. The ions deposit their energy in the outer layers, with a specific deposition of 20 MJ/g, thereby creating a shock wave which compresses the fuel and causes its temperature to rise at the same time, hence initiating thermonuclear fusion burn in the DT mixture.

The energy released, mainly in the form of 14 MeV neutrons, is absorbed in the reaction vessel wall, and is converted to electrical power. With an energy gain (fusion energy beam energy) of 1000 or more, and a repetition rate of one pulse per second, the mean fusion power is 1000 MW, converted to about 400 MW net electrical power via heat exchangers and the usual steam cycle.

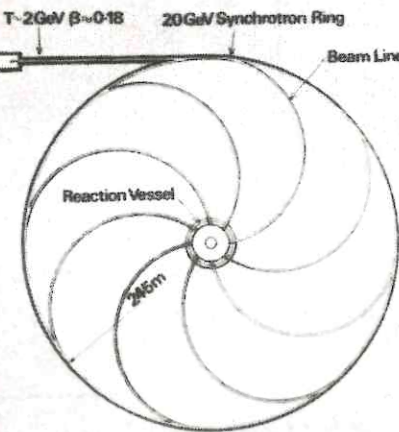
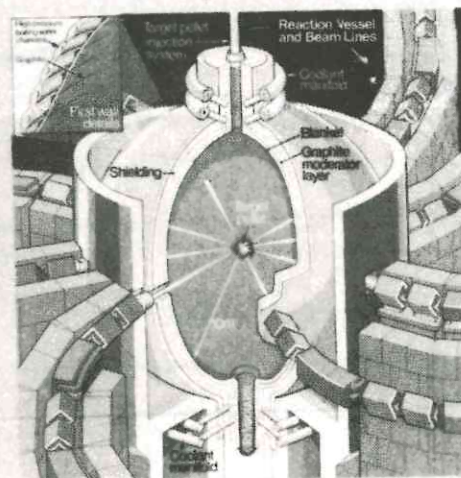
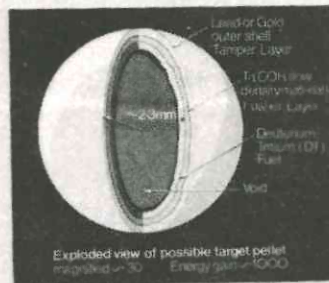


FIG. 1

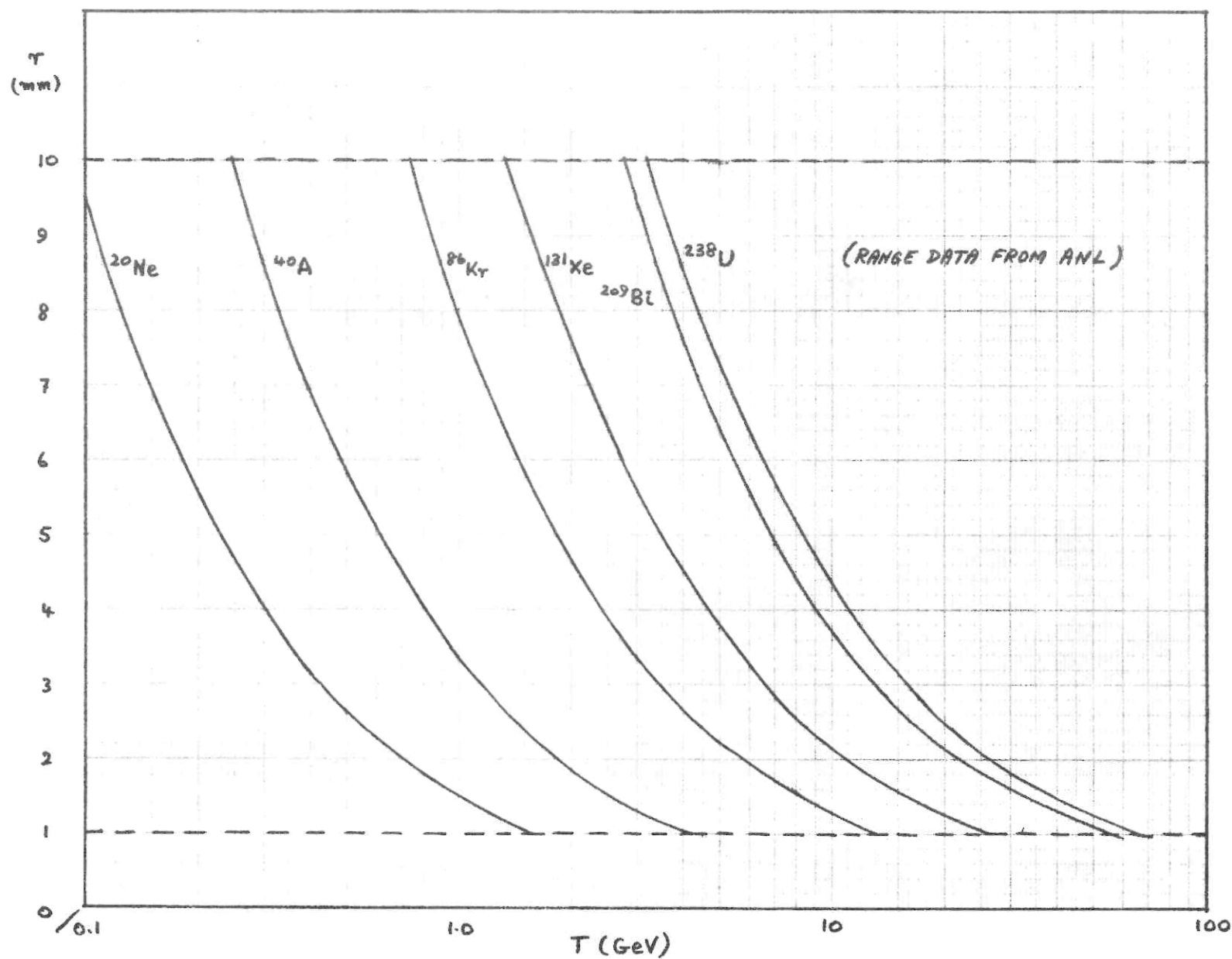


FIG. 2 TGT. RADIUS = SPOT RADIUS vs. KINETIC ENERGY FOR VARIOUS IONS
(1MJ BEAM ON TARGET, 20 MJ/g SPECIFIC DEPOSITION, HEAVY METAL SHELL)

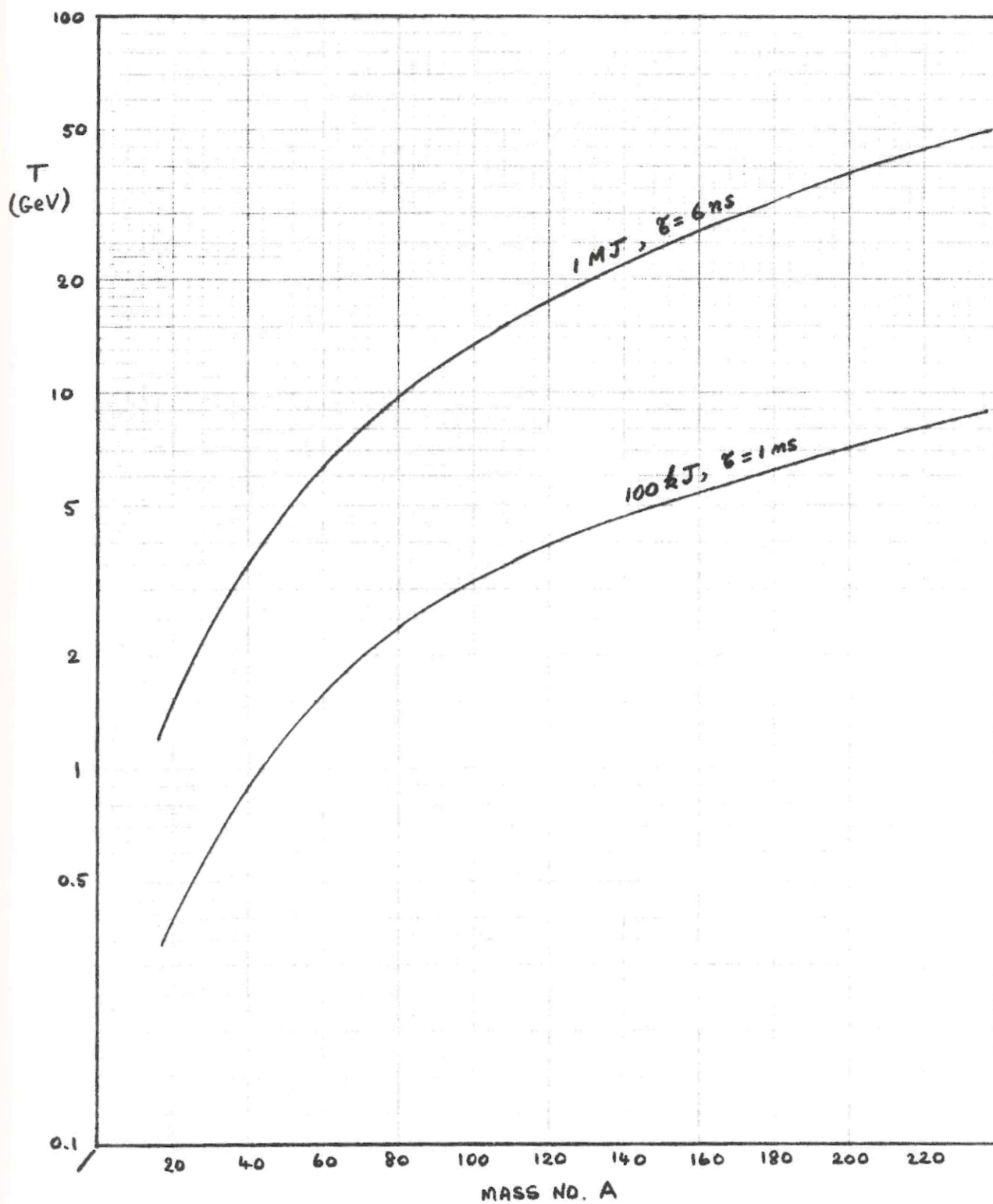


FIG. 3 KINETIC ENERGY vs. ION MASS NO.
 LOW-DENSITY TARGET SHELL, RADIUS $r = 1 \text{ mm}$
 (LIVERMORE DATA)

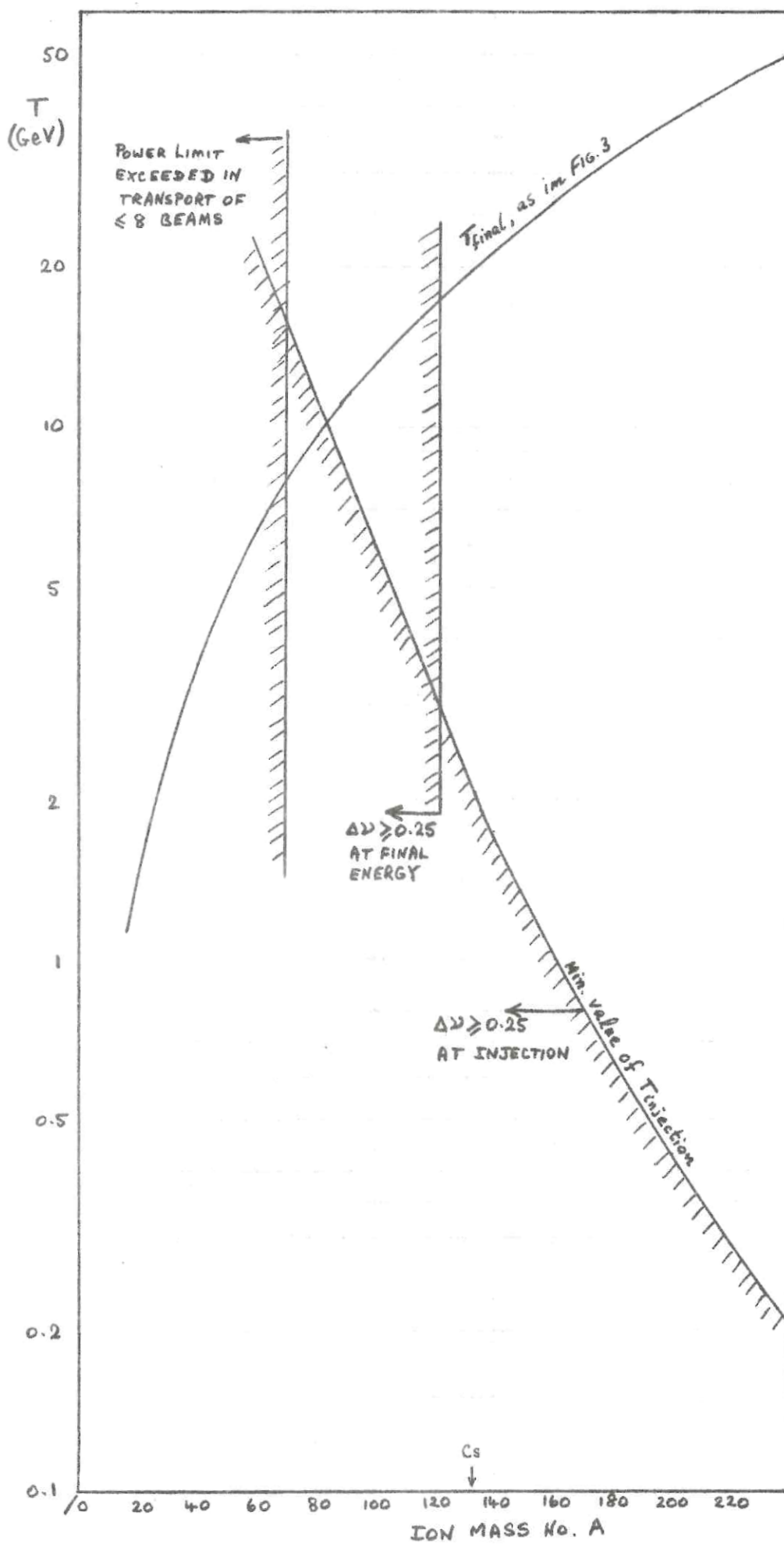


FIG. 4
 EFFECTS OF
 SPACE CHARGE
 LIMITATIONS

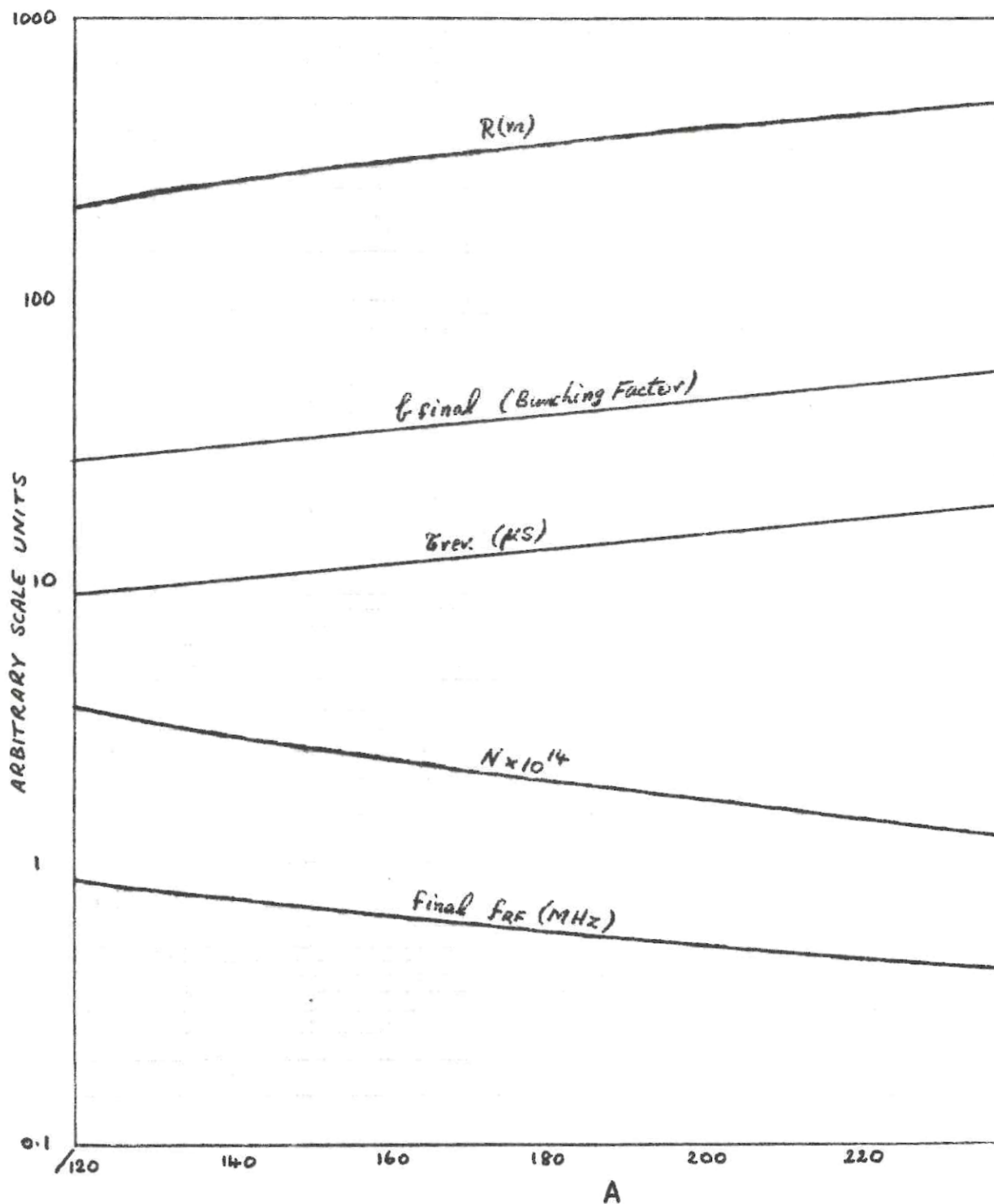


FIG. 5 VARIATION OF SOME RING PARAMETERS WITH ION MASS NO. A

II

TARGET DESIGN FOR HEAVY ION FUSION

T D Beynon

The subjects covered in this talk fall into two broad categories, namely
1) energy production and energy requirements for inertial - confinement pellets and 2) targets for heavy ion beam compression.

1. ENERGY PRODUCTION AND ENERGY REQUIREMENTS

The D-T reaction ($Q = + 17.6$ MeV) is, as in the case of magnetic confinement, the most favourable for net energy production. Using simple arguments in which we ignore hydrodynamic effects, non-linear effects and assume simple energy exchange from heavy ions to electrons to heat the D and T ions, we can easily show that the product of the mass density, ρ , and the radius, r , of a sphere in thermonuclear equilibrium are such that $\rho r \gg 0.1 \text{ g cm}^{-2}$. Defining an energy gain factor $G = \text{Energy from fusion} / \text{Energy in ion beam}$ and a beam coupling efficiency, $\epsilon = \text{Energy in plasma} / \text{Energy in ion beam}$, it can be demonstrated that the product of plasma density n and inertial confinement time τ is such that:

$$n\tau \sim (G/\epsilon) \times 1.8 \times 10^{15} \text{ (cgs)}$$

at a plasma temperature of $T = 10$ keV.

For the Lawson criterion, $n\tau \sim 2 \times 10^{14}$, we therefore require that $G/\epsilon \geq 0.1$. Consequently, at $T = 10$ keV, we obtain the condition that

$$\text{Energy (ion beam)} \sim (G^3/\epsilon^4) (n_s/n)^2 \times 1.6 \text{ MJ},$$

where $n_s = 5 \times 10^{22} \text{ cm}^{-3}$, the solid density of cryogenic D-T, and where $C = n/n_s$ is the compression achieved in the pellet. Contributions to the thermal energy from α -particle and neutron heating (fusion-reaction products) will however give a significant relaxation of this condition, particularly if $G/\epsilon \geq 2$. At $G/\epsilon \sim 4$, for example, this form of heating will double the D-T reaction rate with a corresponding reduction in the ion-beam energy requirements.

2. TARGETS FOR HEAVY ION-BEAMS

Hollow shell targets significantly reduce ion beam requirements compared with solid targets. The high density shell stores kinetic energy during an implosion and produces final temperature and pressure in D-T by transfer

of energy from the shell to the D-T. Thus we regard the compression and heating of D-T as divided into two phases: i) initial compression and heating, followed by ii) adiabatic heating and compression by tamping action of the shell. For ion compression (light or heavy ions) the outer shell of a single shell target is functionally divided into three regions. The outermost region receives little heating and serves basically as a tamper layer. The middle region of the shell contains most of the ion energy deposition via the Bragg peak, and the innermost region remains unheated. This last region then acts as an inner pusher layer which implodes, compressing and heating the D-T fuel. This design is probably more efficient for heavy ion fusion than for laser beam or relativistic electron beam fusion where the energy is deposited in the outer ablation region.

More sophisticated analysis leads to the concept of double or multiple shell designs in which velocity multiplication and pulse shaping can occur. An outer shell of a low-Z low density material with $R/\Delta R \sim 5$ serves as a pusher and a preheat shield, with $\Delta R \sim \lambda$, the heavy ion range. An inter-shell of gas or low density foam serves as a pulse-shaping region and a region which minimizes the sensitivity of the target to Rayleigh-Taylor instability. The inner shell, containing the fuel in the form of a high density gas or fluid, is of a high Z high density pusher with $R/\Delta R < 10$. This shell may also be subdivided to contain a preheat shield against X-rays and fast electrons. The elastic collision of the massive outer shell with the lighter inner shell produces a useful velocity multiplication for the fuel compression which significantly reduces the velocity requirements for the outer shell.

Areas of physics which need urgent attention in the design of single or multiple shell targets include the following:

- i) A detailed understanding of the energy deposition process of the heavy-ion interactions, including the effects of nuclear-breakup and collective coulomb interactions.
- ii) A study of Rayleigh Taylor instabilities and methods of minimizing this effect.
- iii) A study of possible asymmetries arising from multiple beam irradiation.
- iv) A study of the implosion efficiency in terms of ion energy, charge state, focussed intensity, absorber Z and pusher mass.

III

PROBLEM AREAS IN HEAVY ION FUSION

J D Lawson

1. INTRODUCTION

It is now possible to see the broad outline of a concept involving heavy ion accelerators, target pellet, reactor vessel and steam plant which might, after considerable research and development effort, eventually form the basis of a generator of useful power.

A close look at any aspect of this concept reveals a number of difficult inter-related technical problems, all of which will need ultimately to be solved. Our present task is to identify problems which it would be profitable to study in the U.K. at the present time, and to initiate suitable studies. In making this choice, some judgement of the resources likely to be available must be made, and account taken of work at present being done in the U.S.A.

Three main areas of work may be distinguished, these are

- (i) Design of suitable target pellet.
- (ii) Design of accelerator system capable of delivering energy into pellet.
- (iii) Design of reactor system capable of handling and converting to usable form the fusion energy generated in the pellet.

Item (i) is related to work on high density plasma in the Laser Division at Rutherford Laboratory, and also to work at the Universities and Culham; expertise relevant to item (ii) is mainly at the Rutherford Laboratory, whereas topics relevant to item (iii) have been studied mostly at Culham and Harwell.

These items will now be examined individually in more detail.

2. DESIGN OF TARGET PELLETS

Information on target performance and characteristics has been provided by Livermore (Nuckolls and Bangerter) and Sandia (Clauser). This is in the

form of curves and tables which enable energies and currents to be related to target size, energy output, and gain. The more attractive designs, resulting for example in a gain of 1000 from a 1MJ input beam pulse of length 6-10ns, are still somewhat tentative and likely to remain so until more experience is gained with high density targets in laser experiments.

Assessment and understanding of the American work requires study here of the physical processes involved in energy deposition and transfer to the pellet core. Such studies have much in common with those appropriate to laser - plasma interaction and laser fusion.

3. DESIGN OF ACCELERATOR SYSTEM

The essential task here is to draw ions from suitable sources, accelerate them, and focus them on the pellet. Considerable compression both in space and time is required; this must be done within the phase-space constraints imposed by Liouville's theorem. A number of detailed strategies have been proposed, (see for example the earlier paper by King). Time compression involves storage rings and 'bunching' whereas transverse space compression will occur automatically since transverse velocities and dimensions decrease as the longitudinal momentum grows.

Simple estimates have shown that adequate phase-space volume should be available with 'reasonable' systems. Both near injection and at high energies (during and after the final bunching), however, space-charge forces are very high. This means that design of beam transport systems will be difficult, and, in particular, there is danger both of an increase in effective emittance arising from the filamentation of the phase-space volume, and of destructive instabilities. Indeed, an extrapolation of present experience in high current beam transport is required. These problems are not readily susceptible to analysis, and detailed experimental studies with intense heavy ion beams will ultimately be required. Meanwhile, experience of some of these problems could be obtained from studies with electron beams on a more modest scale, using existing commercial electron guns. In particular, predictions of some rather detailed and elaborate theoretical work at Berkeley could be tested.

Apart from these rather general problems associated with the handling of high current beams, many particular problems remain. For example, ion

sources and preaccelerators are needed which produce currents in the range of 50-100 mA at about 1 MeV, with a normalized emittance better than 0.2 mm-mrad, (corresponding to an actual emittance of 50 mm-mrad for Cs at 1 MeV). This requires a fair sized development programme, and in the USA multi-aperture sources, a Penning source with Pierce electrodes, and a caesium surface ionization source are all being studied.

Acceleration and storage of singly charged ions demand extremely stringent vacuum conditions, since stripping cross sections are high. Standards appropriate to the CERN ISR, or even higher, will be required in storage and accumulator rings. In other parts of the system, especially in beam transport lines, the effect of space charge neutralization will need to be understood. This is a problem which does not 'scale', and is difficult to assess independently of the final design.

Another important effect in the storage ring system is loss of particles from the reaction $X^+ + X^+ \rightarrow X^0 + X^{++}$, where X represents the heavy ion. The energy range of interest depends on the energy spread and emittance (or transverse temperature) of the beam; it extends from zero to perhaps as much as 1 MeV relative energy (ie the energy of one particle in a frame such that the other is at rest).

A region where the behaviour is complicated and not yet clearly understood is in the final 5-10 metres between the final focusing lens and the pellet. This involves transient behaviour of a very intense beam in a gas of finite pressure, and represents a complicated combination of beam physics, plasma physics and atomic physics. The problem is difficult to define precisely, and there is always a danger of theoretical overelaboration of unrealistic models. The most relevant experiments to date are those which involve pulsed intense relativistic electron beams. Preliminary studies at Livermore indicate that both space charge and current neutralization will occur if the ambient pressure in the chamber exceeds 10^{-2} torr, and that multiple scattering will be important above 10 torr. If this is correct, then 'single particle' optics can be used, and the problem is much simplified.

4. REACTOR DESIGN

Many problems need to be faced and resolved before a suitable reactor environment can be specified for an inertial fusion system. Reactor studies

inevitably require the coordination of a large group of specialists, since so many disciplines are involved. These include: mechanical and electrical engineering, materials science, heat transfer, radiation damage and activation, fatigue problems, neutronics, tritium handling and lithium chemistry. Many of these topics are common to magnetic confinement systems.

Large scale studies for a laser fusion reactor have been made, particularly at Wisconsin, and implications for heavy ion fusion have been studied at Livermore. Current emphasis is on schemes involving lithium walls, in the form of a falling curtain of liquid or ceramic balls containing a lithium compound.

5. CONCLUSIONS

It is evident that much requires to be done to establish that heavy ion fusion represents a real possibility as a future energy supply. It is easy to write down long lists of problems and unknown factors, but more difficult to decide on relatively small scale activities which are profitable at the present time, particularly in view of the much larger scale of the American effort.

We must clearly educate ourselves in order to make reasonable critical judgements on the programme as a whole, but we can also contribute to those areas where specific problems occur which correspond to particular enthusiasms and expertise which exist in the U.K.

A table follows giving the main areas of physics and technology required; points of special interest, where we might reasonably make a detailed contribution are also noted.

AREA	TOPICS ON WHICH WORK MIGHT BE DONE
Pellet design	Physics of energy deposition from ions Comparison with laser pellets.
Accelerator strategies	Evaluation of general constraints and estimation of efficiency.
Beam physics	Studies of beam transport with high space charge.
Atomic Physics	Measurement and calculation of charge exchange cross sections.
Plasma physics	
(a) High density (pellets)	
(b) Low density (Reactor environment, beams, sources).	
Ion source technology	
Accelerator technology	
Reactor technology	
Relation to overall energy strategy.	

Action is already being taken on several topics listed in the second column. Rutherford Laser Division and Birmingham University are interested in those shown against Pellet Design. Work on the topic associated with Accelerator Strategies is underway at Rutherford, and some theoretical work has been done on 'Studies of Beam Transport with High Space Charge'.

There is scope also for a good experimental programme on beam physics using electron beams, but we require someone who wishes and is able to do it.* Finally, a field where the UK is particularly strong is that of atomic physics, and work on charge exchange cross-section measurement is already being planned at Newcastle and Belfast.

* Work reported since the meeting.

Experimental work on the transport of electron beams is planned at Maryland, we hope to maintain active contact with this.

Computational work at NRL, Washington, using powerful self-consistent particle simulation techniques indicates emittance growth of an initial K-V distribution by a factor of order 2 or more (depending on parameters) and then propagation in a steady state.

POINTS ARISING DURING DISCUSSIONS

During the discussions that followed the presentations the following points were made:-

- (i) In the USA between 50 and 100 people at various laboratories were working in the field, with a budget last year of around \$6M.
- (ii) In reply to a question, King said that no one has as yet come up with a feasible proposal for a collective ion accelerator.
- (iii) Energy Balance. The question of overall energy balance in accelerator plant was discussed. With a storage ring system around 50% of the RF energy would get into the beam. Best guess is that overall efficiency would lie between 15% and 50%. This compares with a laser efficiency of 10% overall, and difficult to go higher.
- (iv) Pellet Design. It was stated that an energy gain of 1000 implies a propagating nuclear burn and complex pellets. What has not to be lost sight of is that pellets may not work as predicted and accelerator requirements could therefore change in mid-stream. The shape of the energy pulse is important and must be included in the design of the accelerator. Neutron pre-heating of pellets could be a problem.
- (v) Ion Source Technology. The main centre for this work in the UK at present is Culham Laboratory, and includes development of high intensity and heavy ion sources. Some work is also going on at Birmingham University on duoplasmatron sources. At AERE Harwell there is source development in connection with ion-implantation work.
- (vi) Atomic Physics. The Newcastle and Belfast University Groups are strong in measurements of ion-ion cross-sections, and there was justification for additional work on this topic. It was stated that Belfast will shortly be looking at caesium/caesium reactions. The need to cover the full energy range up to 1 MeV centre of mass was stressed. There may be arguments for even heavier ions.

- (vii) Not enough is known about what happens when very dense ion beams interact with dense matter. It is worth examining what experiments are needed, how these compare with what can be done at present, and what can be learnt by scaling. It was suggested that an interlocking strategy involving both pellet and accelerator design should be worked out. A difficulty arises, however, that if the particle energy and total energy in the pulse are scaled down, the problems associated with beam focusing and the production of a short pulse become extremely severe. This is in contrast to the situation when lasers are used; sharp focusing and short pulses are readily obtainable at intermediate power levels.
- (viii) Problems associated with the transport of high current beams could be tackled on apparatus of modest size. Experiments must be carefully designed; space charge neutralization phenomena for example cannot readily be scaled, they depend very much on the details of particular apparatus.

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