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HEAVY ION INERTIAL FUSION - AN OVERVIEW

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Résumé - Des ions énergétiques lourds représentent une alternative au laser et aux ions légers en tant que "drivers" pour fournir de l'énergie pour la fusion en confinement inerte. Pour induire l'ignition des cibles contenant le combustible thermonucléaire, une énergie de plusieurs mégajoules doit être focalisée sur une cible avec un rayon de quelques millimètres, dans le temps de quelques dizaines de nanosecondes.

Une étude sérieuse sur l'utilisation d'ions lourds en tant que "drivers" pour produire de la puissance utile de cette façon est en cours depuis sept années, bien que le financement ait été à un niveau bas. Dans cet article, les spécifications requises pour les cibles, l'accélérateur, et le récipient du réacteur pour contenir l'explosion thermonucléaire sont mises à l'étude, et quelques uns des problèmes qui doivent être résolus avant que la construction d'une centrale ne puisse être envisagée de façon réaliste sont discutés.

Abstract - Energetic heavy ions represent an alternative to laser light and light ions as "drivers" for supplying energy for inertial confinement fusion. To induce ignition of targest containing thermonuclear fuel, an energy of several megajoules has to be focused on to a target with radius a few millimetres in a time of some tens of nanoseconds.

Serious study of the use of heavy ions drivers for producing useful power in this way has been underway for seven years, though funding has been at a low level. In this paper the requirements for targets, accelerator, and reactor vessel for containing the thermonuclear explosion are surveyed, and some of the problems to be solved before the construction of a power station can realistically be contemplated are discussed.

1. INTRODUCTION

The idea of using beams of heavy ions as an alternative to laser light to provide the energy for inertial confinement fusion (ICF) was first given serious consideration seven years ago, at a two week study held at Berkeley in July 1976 /1/. Members of the accelerator community emphasized two important advantages of accelerators compared with lasers. First, the efficiency of accelerators for converting electrical energy into a beam of particles is potentially much higher than the efficiency of lasers. The need for a high driver efficiency was becoming more pressing since the target gain, defined as the ratio of thermonuclear energy produced to incident photon energy, was turning out to be lower than originally hoped. A second advantage forseen was that operation of accelerators at repetition rates of several per second, a necessary condition for an economic power station, presented no great problem, whereas for lasers the difficulties appeared to be severe.

Both these advantages are important for power production, though neither is essential for the immediate aims of the US inertial confinement programme, which are related to weapons research.

At the time of the Berkeley workshop, electrons of energies of a few MeV has also been considered as ICF drivers; experiments were already being done in the USA and USSR /2/. Such beams can be produced with high efficiency from diodes, driven by discharging a coaxial line which has been charged by a Marx generator. The technique is relatively cheap and simple. Unfortunately electrons have turned out to be unsuitable, one reason being that their range in targets is too long; (the question of particle range is discussed later, in section 3). Following the invention of several types of ion diode, research is continuing with light ions accelerated across a single gap /3/. As with lasers, operation at high repetition rate presents difficulties. More fundamental is the problem of focusing the beam down to the small size required to ignite a target pellet.

The situation with regard to heavy ions at the time of the Berkeley workshop was summarized in the digest of ref.1. "The central result was an affirmation that ion beam fusion power merits serious attention. The accelerator experts found no fatal flaws in the systems they studied .... Target experts developed pellet requirements in which they have high confidence, and also less demanding targets that may be acceptable. Reactor designers began to consider a wide range of concepts .... Considerable enthusiasm was generated". This quotation continues with the cautionary statement: "However, it is clear that present information is inadequate to establish the technical feasibility of ion beam fusion with reasonable confidence, or to select the optimum type of accelerating system ...". Six "areas requiring research and development" are then identified.

The general sentiments expressed in this quotation remain valid, though ideas on what the main problem areas really are have shifted somewhat; some initial worries have disappeared, while others have appeared to take their place.

Although much has now been clarified, largely as a result of further workshops /4-7/, this has nearly all been as a result of theoretical studies; very little experimental information of direct relevance has yet been gained. This can partly be attributed to meagre funding, but one outcome of the past few years has been the realization of how hard it is to do meaningful, relevant, experiments without the expenditure of a great deal of money. This is a reflection of the fact that in all three areas, targets, accelerators and reactors, the requirements of a working power station represent a considerable extrapolation from present experience. Although this extrapolation is great, the physical principles involved are in general well understood. Despite this fact, the inherent complexity is such that reliable quantitative predictions cannot yet be made.

In this talk an outline will be given of the physical principles that determine the design of the target, accelerator, and reactor vessel, together with some discussion of designs forseen at present, and requirements for future research. First, however, it is appropriate to examine what is needed for a future power station. This gives an indication of the order of magnitude of the principal parameters, and the way in which the components are interrelated. Two attempts have been made to provide a scenario for a complete power plant /8,9/. Both require modification before they can be considered as convincing.

2. COMPONENTS OF AN ICF POWER STATION WITH HEAVY ION DRIVER

The mode of operation of some future power station can be summarized as follows. Power is produced by igniting small pellets (or 'targets') containing a thermonuclear fuel. In the first instance this will be a mixture of deuterium and tritium. Ignition is achieved, as described later, by bombarding these targets with intense pulses of heavy ions. The energy explosively liberated from the fuel in the targets is contained within a suitably designed reactor vessel, in which provision is made for breeding more tritium from lithium. Heat generated is used to raise steam for the turbines in the usual way.

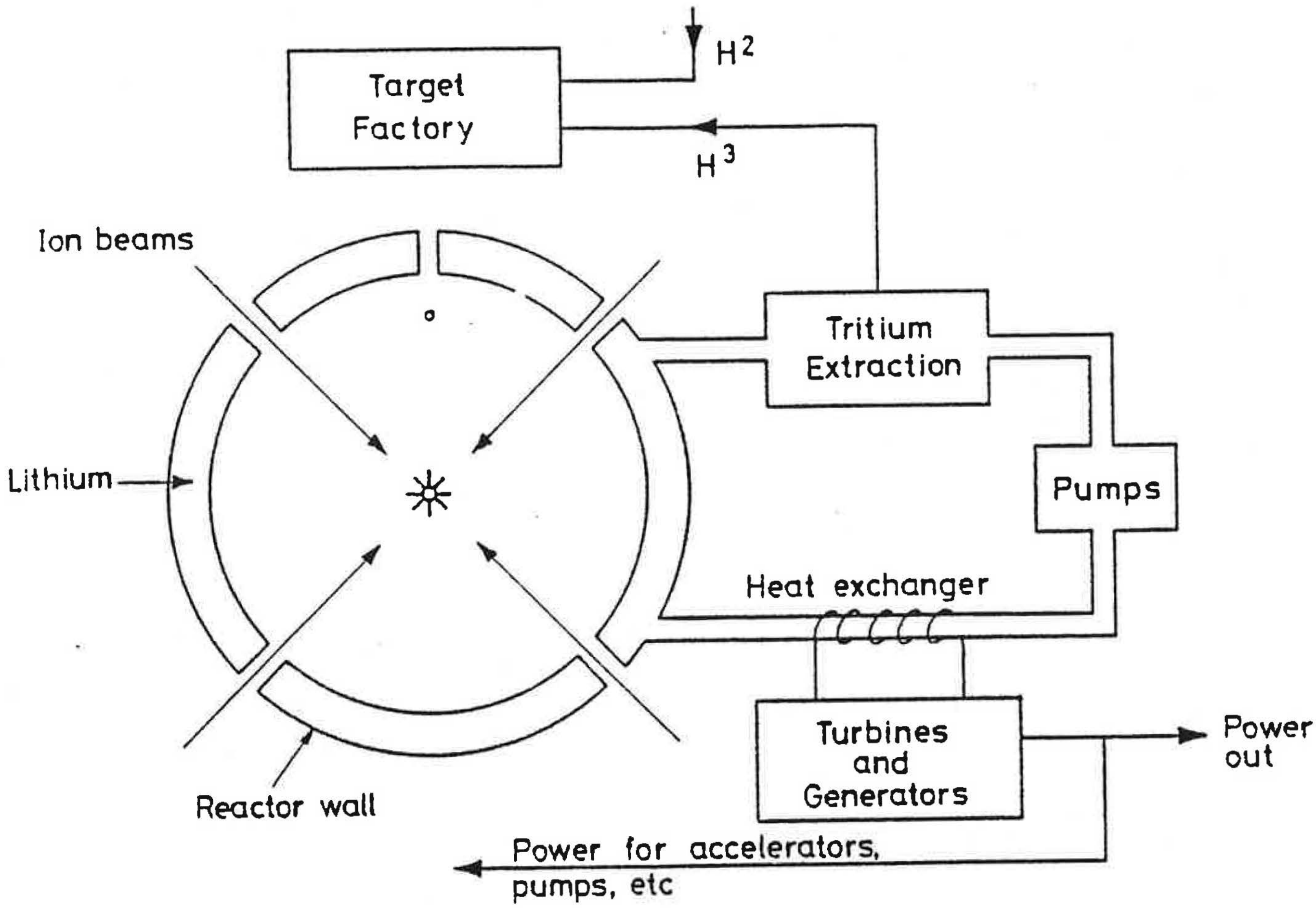

Fig.1. Essential components of power station.

The disposition of these components is sketched schematically in Fig.1 for a typical system. The output of the power station is assumed to be at least 1 GW electrical. It might be desirable, especially for a 'demonstration' system, to have a lower value, perhaps 300-500 MW. Unfortunately, however, as with magnetic fusion, operation at lower output, (clearly possible by reducing the pulse rate), would be uneconomic. Scaling down the size of the targets, and hence also of the reaction chamber, makes the achievement of positive energy balance more difficult.

The values of the leading parameters now anticipated are given in the tables below. The factors which determine them are discussed in later sections.

Parameter Range for Power Plant

Electrical Output, W	1-5 GW(e)
Pulse repetition rate	2-20 Hz
Energy released per pulse	1-5 GJ
No. of reaction chambers	1-4
Chamber radius	5-10 m
No. of beams on target	8-40

Parameter Range for Driver and Target

Energy in beam pulse	1-10 MJ
Beam power	100-500 TW
Pulse length	10-50 nsec
Ion energy (high Z)	5-15 GeV
Particle charge state	1
Particle current on target	10-50 kA

The main difference between these figures and those envisaged at the 1976 workshop is that the ion energy is considerably lower. This arises from a re-evaluation of the optimum parameters required for the target, presented at the 1979 workshop /6/, and gave rise to a revision of the anticipated accelerator parameters. Gains from the lower ion energy were more than offset by the increased effect of space-charge, and larger un-normalized emittance of the final beam.

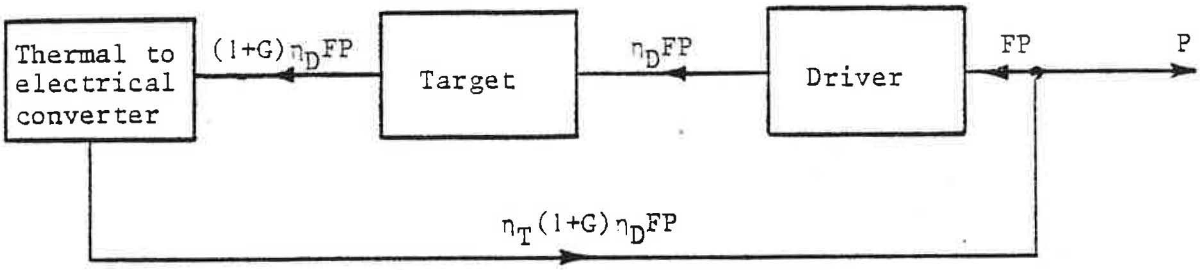

Fig.2 Energy flow diagram.

The energy flow diagram for the power plant in Fig.1 is shown as Fig.2. F represents the ratio of recirculating power to output power, η_D is the ratio of beam power to that supplied to the accelerator plus other auxiliary power (e.g. for pumping lithium), G is the target gain defined as thermonuclear energy released to energy carried by the driver beam, and η_I is the conventional thermal efficiency. The condition for power balance at the junction point yields the relation:

$$F[\eta_T\eta_G(G+1)-1] = 1 \qquad (1)$$

Making the assumptions that F as high as 1/3 is tolerable, and $\eta = 0.4$ yields the important constraint $\eta_D(G+1) > 10$. It is the fact that values of G for inertial fusion are much lower than had been originally hoped /10/ that demands large η_D, and hence favours particle beam fusion.

In the following sections, individual components of the power station will be considered, before again returning to a discussion of the complete system.

3. TARGET CHARACTERISTICS

We consider first a simplified idealized target consisting of a mixture of deuterium and tritium surrounded by a spherical shell. A pulse of energy incident on the shell and absorbed near its surface heats the material of the shell, which then ablates; the resulting inward 'rocket' force compresses and heats the fuel, which then ignites yielding fusion energy. The thermonuclear process is the familiar 'DT reaction',

$$H^3 + H^4 \rightarrow He^4 + n + 17.6 \text{ MeV}.$$

14 MeV is carried by the neutron, which first deposits most of this energy as heat in the reactor vessel walls and lithium blanket, and then is absorbed by the lithium to produce a further atom of tritium.

Clearly it would be advantageous to have very small targets; a rapid succession of small explosions is easier to contain than less frequent larger ones. As might be guessed from the relative ease of making hydrogen bombs, the problem of ignition becomes harder as the target size is decreased. This may readily be seen from a discussion of the scaling laws. At a given temperature, the reaction rate for fusion is proportional to the square of the density, $n\tau$. After a time r (not so large that an appreciable amount of fuel is consumed) the number of reactions is $n\tau$, so that the fraction of fuel burnt is proportional to $n\tau$. This product is therefore a measure of the ratio of energy released to thermal energy in the target, and for a net energy gain must exceed some minimum value. Numerically this is of order 10^{14} $cm^{-2}sec^{-1}$ for the DT reaction. In an inertially confined target τ is the 'disassembly' time, which is proportional to the target radius r. The quantity n can then be written ρr, a figure of merit related to energy gain. For 'breakeven' ρr is about 0.1 gm cm^{-2}; under these conditions the range of the α particles produced in the reaction is greater than r, and little of the charged particle energy is deposited in the hot plasma. When ρr = 3 gm cm^{-2} the α particles are contained and a substantial fraction of the neutron energy is deposited directly in the plasma, and a propagating burn occurs. This condition is required for high gain pellets.

To examine target scaling we set

$$\rho r = \frac{m}{(4/3)\pi r^2} = C \tag{2}$$

so that for scaled targets $m \propto r^2$. Smaller mass implies smaller radius. Since $m \propto \rho r^3$,

$$\cdot\ \rho \propto \frac{1}{r} \propto \frac{1}{m^{1/2}} \tag{3}$$

Decreasing the target mass implies decreased radius and increased density. In pratical high gain targets densities of some 10^3-10^4 times the solid DT density of 0.2 gm cm^{-3} for input energies of a few MJ are necessary. The compressed radius is of order 1/30 mm.

These scaling laws, plus others that may readily be verified may be tabulated:

Quantity	Dependence on mass
Radius of target	$m^{\frac{1}{2}}$
Density of target	$m^{-\frac{1}{2}}$
Energy to heat target	m
Power during heating pulse	$m^{\frac{1}{2}}$
Power density at surface during heating pulse	m^{-1}

These scaling laws are crude, and take no account of the sophisticated dynamics and physics of the compression process in real targets. They do, however, illustrate the nature of the trade-offs to be encountered in target design. For large targets a massive driver system is required, and the explosion is difficult to contain. For small targets, on the other hand, it is difficult to focus the ion beams to provide the high energy density needed to produce adequate compression and the energy gain is low. The range of target sizes that will fit the parameters suitable for a power station, (if it exists!) is narrow.

The first published estimates of the properties of ion driven targets were given in 1975 for light ions by Clauser /11/, and much has been published since. The fuel compression and hydrodynamic behaviour of ion and laser driven targets have much in common, but the energy absorption mechanism is, of course, entirely different. For ions this is basically the classical collisional slowing down mechanism first discussed by Bohr. There are complications associated with the stripping of successive electrons from the incoming ion, and the heating of the target, though collective wave processes that occur in the much more complicated laser heating are not important.

No attempt is made here to describe the details of target physics or target design, but some general comments are in order. A great deal of detailed work on many designs indicates that an input energy of 'a few' MJ at least is required for high gain. Further, the target mass must be limited to produce a 'specific energy deposition' of at least 20 MJ g^{-1}. This implies that the ion range must not be too large, and hence a limitation to the ion energy. The figure of 0.1 gm cm^{-2} gives energies of about 10 GeV, 1 GeV and 30 MeV for uranium, argon and helium respectively.

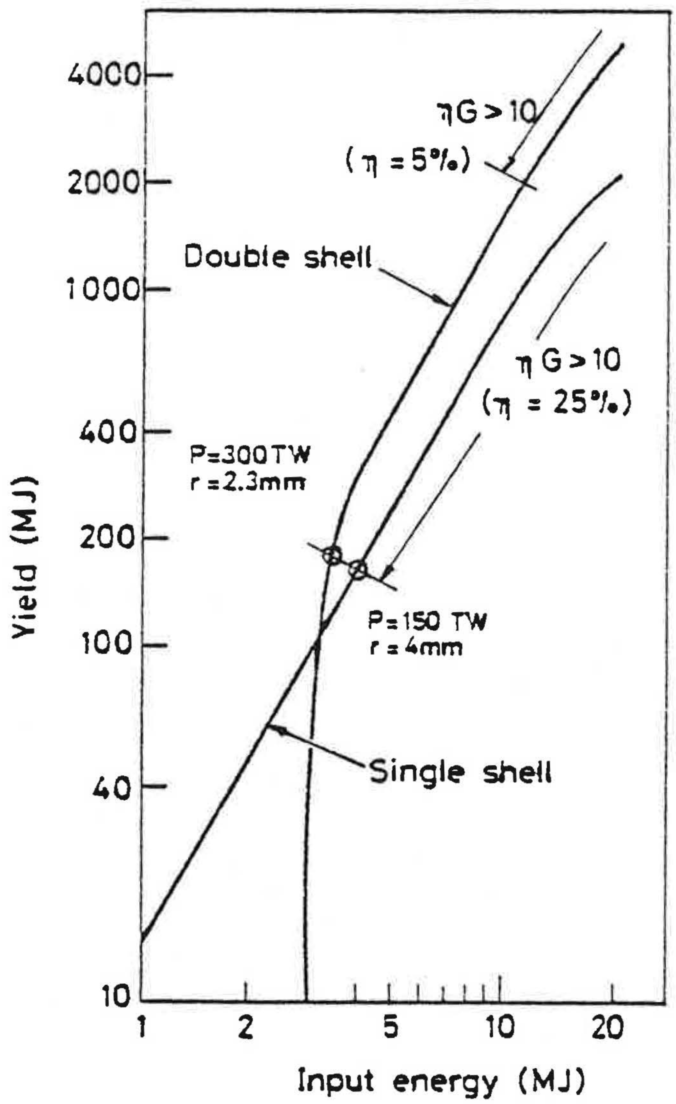

Fig.3. Target yield as a function of input energy for typical single and double shell targets. Values of power and spot radius are shown where $\eta_D G = 10$.

High gain targets are more complicated in design than the simple DT mixture surrounded by a shell discussed earlier. Two designs with spherical symmetry have been described by Bangerter et al /12/. One of these contains a beam deposition layer, inside which is a preheat shield. The shield consists of a low Z layer seeded with high Z material, to prevent X-rays entering the fuel and heating it prematurely. Inside this shield is the fuel, int he form of a hollow sphere of solid DT. About half the pellet volume is empty space. The double shell design has in addition, suspended at its centre, a further small hollow sphere of solid DT inside a thin high Z tamper. In this target the outer sphere moves inward and collides with the inner target, compressing and igniting the fuel therein. The burning then spreads to the outer fuel layer. Double shell targets are capable of higher gain, but for a given energy input they require higher power and therefore a shorter pulse. The beam pulse needs to be shaped in order to secure maximum gain.

A set of curves relating gain to input energy for these targets is given in ref.12. Power requirements are also shown. Targets are characterized by a scaling parameter $r^{3/2}R$ over the range 0.005 to 0.04, where r is the spot size in cm and R the ion range in gcm^{-2}. To obtain high gain, small values of $r^{3/2}R$ are required. To obtain the same value of gain at the same input power, smaller $r^{3/2}R$ is required for the single shell target.

Making R small means that low energy ions are required; for given power this increases the current and makes space-charge limits in the accelerator more severe. Making r small implies small spot size, with attendant difficulties of final focusing.

Orders of magnitude for parameters relevant to fusion power stations taken from the curves of ref.12 are given in the table. The curves are labelled 'best estimates', and lie well below a further curve labelled 'ideal'. A comment on this will be given later. Uranium ions at 10 GeV (R=0.1) are assumed, S and D denote single and double shell targets.

Beam energy, MJ	Spot radius, cm	Gain	Peak power, TW
2S	0.16	30	160
4S	0.32	50	330
4D	0.29	80	180
6S	0.45	60	440
6D	0.32	130	220
6D	0.45	90	190
8S	0.51	85	520
8D	0.45	130	280

Double shell targets are obviously more difficult to fabricate, but to obtain adequate gain to satisfy the criterion $\eta_D G > 10$ with a single shell target requires high input energy and peak power. The double shell requires less power and energy input for a given gain than a single shell target with the same spot size.

Fig.3 shows a curve due to Herrmannsfeldt /13/ which summarizes the position. Target yield is plotted against input energy, for typical single and double shell targets. Lines corresponding to $\eta_D G = 10$ for $\eta_D = 5\%$ and 25% are shown; only those values of input energy above the points where these lines cross the curves can be used in an economic power station. Values of spot size and power at the crossing points are indicated.

In the two large scale studies that have made so far of complete HIF systems, comprising accelerator, target, and reactor, target performances better than those indicated in ref.12 have been assumed /8,9/.

The question arises, how reliable are the many calculations of target properties that have been made? The regimes under study lie far beyond what has been achieved experimentally. Will the gain turn out to be lower than anticipated, as happened with laser targets? Or is there scope for good fortune or inventive ideas that will eventually produce much more satisfactory solutions than those indicated in ref.12? These are open questions, judgements and opinions vary. Further results from high power laser experiments will certainly be relevant, but because of the different energy deposition mechanism they can hardly be expected to yield all the information that is required.

Targets considered so far have been spherically symmetrical in form. To make final focusing of the ion beams easier a large radius is desirable. Because of the constraints on the specific energy deposition this implies that for a given input energy of alarger target has thinner shell and a smaller ratio of shell thickness to target radius. A limit to the smallness of this ratio is imposed by consideration of stability; when a light fluid is accelerated against a heavier one the classic Rayleigh Taylor instability takes hold, the system departs from spherical symmetry and the compression is spoiled. This is an important constraint to target design not adequately modelled in some of the simpler computer codes that have been used. The curves marked 'ideal' in ref.12, which give gains better by a factor of order 10, are the results of one dimensional calculations, several ideal assumptions are made and considerations of stability are not included; there is hope therefore of higher gains than those given in the table if instabilities turn out to be less severe than the more complete calculations indicate.

An important question relating to the symmetry of the implosion is the number of beams required and their disposition. For laser driven targets the hot coronal region smooths out the inhomogeneity. For ions, however, which penetrate into the shell before losing all their energy this does not happen so readily. The question, though relevant to accelerator and reactor design, may not be important in the present context if the classified 'hohlraum' type of target is used. In such a target the beam energy is converted into soft X-rays contained in a black-body cavity, and spherical symmetry is automatically assured even if only two beams are used.

The existence of classified target designs clearly makes the target problems more difficult to assess from the 'outside'. It is understood, however, that the general orders of magnitude exhibited in ref.12 are not greatly affected.

No detailed discussion of target physics has been given here, but a great deal has been published both in the USA and Europe /14,15/, where several flourishing independent studies are in progress. During the last few years expectations have not changed greatly, and it is agreed that earlier calculations were incomplete and produced rather optimistic results. There is still, however, a large gap between hypothetical high gain targets and what has been demonstrated experimentally, even in the heavily funded laser and light ion programmes. There remains scope for varying judgements (and hopes!) of whether the present 'best estimates' turn out to be reasonable. Meanwhile there remains scope both for further theoretical assessment, and experiments to provide information for these theoretical studies.

One question that must be borne in mind when consideration is given to a practical power station is the cost of the pellets. This must be brought down to a few cents (US). Five pellets per second at 10c apiece represents over $10M for one years supply. Methods for manufacturing targets are described by Sherohman /16/.

4. REQUIREMENTS FOR THE ACCELERATOR

The task of the accelerator is to provide particle beams of the required energy, of sufficient intensity that the very stringent requirements discussed in section 2 can be met. Essentially the problem is one of energy compression. Ion beams are drawn in a relatively leisurely way from large ion sources, and energy is supplied to them during the period of acceleration. The energy residing in these particles has then to be delivered to a very small target in a very short time.

Techniques for accelerating and manipulating charged particle beams are well established, and highly sophisticated. HIF demands conditions which lie well beyond what has actually been achieved, but it is anticipated that the appropriate extrapolation of existing concepts will enable the technical problems to be solved. To find out whether this can indeed be done, at a level of cost and complexity that might someday be acceptable in a power station, is one of the objectives of the present HIF accelerator research programmes in the USA, Europe and Japan. A second objective is to design a machine that will enable useful experiments on the interaction of ion beams with hot plasma to be studied, the so-called 'High Temperature Experiment' now being actively planned.

The present discussion represents an attempt to forsee the type of accelerator installation that would be required for a power station with parameters already listed in section 2. Before looking at details, it is worth examining the constraints in a general way. Since the system is an optical one, the quality of the initial beam (specified by its emittance) and the nature of the aberrations between source and target determine whether the required spot size and pulse shortness can be achieved. This problem can be quantified in terms of the effective volume that the beam particles occupy in six dimensional phase space. Liouville's theorem ensures that the actual 'microscopic' phase space volume is conserved, but the 'effective' volume, which is everywhere convex and encloses all the points can grow as the phase space undergoes filamentation. Account can be taken of this by introducing 'dilution factors' appropriate to the various steps involving beam acceleration and manipulation. Such an analysis has been given by Bangerter et al /17/. The initial beam quality from the ion source is expected to be adequate by a large margin, but the appropriate dilution factors are very difficult to evaluate analytically, and more experimental information is needed.

The problem is made especially difficult by the fact that at the high current levels required, the electrostatic space charge forces are considerable, and determination of the beam behaviour involves the finding of self-consistent solutions to the equations determining the fields and the particle motion. The beam behaviour determines the space charge forces, which in turn determine the behaviour of the beam. In general solutions can only be found by computation (which can be very demanding of computer capacity) or by experiment. Analysis of the limits to the current which can be transported in beam lines /18,19/ and computations which include situations not amenable to analysis have been made /20,21/; experiments are underway /22-24/ and others are planned /25/. None of these approaches is easy, and time will be required for an adequate understanding of the situation to be achieved.

Despite these basic uncertainties, it is of importance to make 'informed guesses', and to try to forsee what an actual accelerator installation might look like. Such information is needed to allow initial cost estimates to be made, and to suggest specific lines of research and development.

Many 'scenarios' for possible accelerator configurations have been put forward since the original concept of heavy ion fusion emerged. These have been steadily modified or abandoned as new ideas have appeared and the nature of the constraints to be met has become more clearly appreciated. This proces is still continuing as difficulties with existing scenarios becomme apparent and the constraints tighten.

Two different approaches to the accelerator problem are being evaluated. One of these, being pursued mainly in Europe and Japan, makes use of conventional components, namely r.f. linacs and storage rings. After a series of manipulations (detailed below) particles are stored in a group of storage rings, they are then bunched, extracted, further bunched and transported down a number of parallel beam lines, to be focused finally on the target. In the USA an alternative approach is being pursued. This is based on the induction linear accelerator, where the accelerating field is produced inductively rather than by means of radio frequency power /26/. Such accelerators have been used for electrons, but the application to heavier particles is still very much in the exploratory stage. Since very high currents can be handled by this method, storage rings are not needed; bunching of the beam is, however, necessary.

Schemes using synchrotrons were studied until about 1979, when it became evident that the energies had to be lower and the currents higher than had earlier been assumed /27,28/. Injection then became more difficult, and the particular advantage of synchrotrons for accelerating efficiently over a large energy range could no longer be so well exploited.

More detailed discussion of the two current approaches follows in the next two sections.

5. LINAC AND STORAGE RING SCHEMES

Several ways of using r.f. linacs and storage rings to provide the required bunched pulses of ions for transportation to the target have been proposed /8,9,29/; at the present time none of them is without challenging problems which arise as a result of space charge forces somewhere in the system. Nevertheless the broad features of what is required are now clear. The most studied of these schemes is the German-Wisconsin 'Hiball', (Heavy Ion Beams And Lithium Lead), presented and examined at the Darmstadt symposium in 1982 /7,9/. One important result which came from this discussion was that with the doubly charged bismuth ions originally proposed, the space charge was so severe that the final bunching could not be carried out; it is now generally assumed that, despite the lengthy linac needed for unit charge state, a value exceeding unity is unacceptable. Changes are accordingly being made to the Hiball parameters /30,31/.

A brief description will now be given of the main components for the linac-storage ring scheme. In the absence of an accepted definitive design, orders of magnitude only are given. Most of the acceleration is carried out in a single Alvarez type linac of length 3-5 km, operating at a frequency of order 300 Mhz. Up to energies below a few percent of the total, where the ion velocities are less and space charge limitations more severe, parallelling of linacs is required. Moving towards the source a 'tree' of two, four, eight etc. up to perhaps 32 each fed by its own source is required. The design of these early linacs differs from that of the main linac; the source will be immediately followed by the recently developed radio frequency quadrupole (RFQ) linac /32/, followed in turn by Wideroe linacs. The operating frequency is increased by two per stage, so that all the radio frequency 'buckets' are utilized. Beams from the individual linacs are combined using 'funnels'. Currents from the ions sources might be tens of milliamps from each source, with hundreds of ma at the output to the linac. This current has to be increased by a factor of order 10^5 between the linac exit and target.

Methods available to accomplish this include multiturn injection into storage rings, bunching in the storage rings, and bunch compression in the final beam lines. Two stages of multiturn injection can be envisaged; in the ring, turns centered on the median plane are accumulated to form a flat ring, (as round the planet Saturn). These are then extracted in a single turn to form a flat ribbon shaped beam, which is then rotation from a horizontal to vertical plane, and injected into a second ring. The ribbon is 'wound up' to fill all the available aperture. Because of the finite beam emittance and the existence of repulsive space charge forces a number of rings will be required to accommodate the required current. The revised Hiball design, for example, has one large 'accumulator' ring of radius 590 m, ten storage rings and ten buncher rings each of radius 120 m. The buncher rings contain r.f. cavities to bunch the beam, this bunching occurs partly in the ring but continues down the beam line towards the target, possibly aided by the installation of additional buncher units. In addition to the components described, a debuncher is needed after the linac to reduce the momentum spread to about 1 part in 10^4, this is necessary if the succeeding operations are to be accomplished satisfactorily.

A great deal of detailed work is needed to establish whether the operations outlined above can be carried out in such a way as to produce an acceptably short and adequately focused pulse of ions on the target. Every indication is that the task is a formidable one; there is scope for emittance growth at all points where beam manipulation occurs, for example at the funelling points in the linac tree and at injection to and extraction from the rings, and also in the rings themselves. In order to minimize any growth arising from the resistive wall microwave instability in the rings, and resonance crossing during the final bunching, it is essential to act fast and to leave the particles in storage for as little time as possible. (The introduction of energy spread to combat the microwave instability is not permitted since the chromatic spread would impair the final bunching and focusing). Dwell times of the order of 1 ms are envisaged in the revised Hiball scheme. These considerations suggest a higher linac current, so that less turns are required in the rings; indeed, the suggested modification to Hiball specifies 660 mA, and increase of four over the original design, but this makes the linac very expensive and the question is still under consideration. An optimum 'sharing of difficulties' between linac and storage rings must be negotiated.

A proper appreciation of the scale and nature of these difficulties can only come from detailed calculation, involving much numerical computation, and experimentation in the appropriate parameter regime. In this connection, the proposed experiment on the Rutherford Appleton Laboratory Spallation Neutron Source seems particularly appropriate /25/.

The question of the final beam transport to and within the vacuum chamber, and vacuum requirements within the rings and beam lines are discussed in later sections.

6. THE LINEAR INDUCTION ACCELERATOR

The use of induction linacs for accelerating electrons is a well established art. Electrons pass through a succession of independently excited gaps, where the accelerating field is provided by the changing flux in a core surrounding the orbit. The impedance of such devices is low, and they are therefore suitable for accelerating high currents. The FXR machine at the Lawrence Livermore Laboratory, for example, accelerates 4kA of electrons at a repetition rate of one pulse per second, though the pulse length is only 60 nsec /26/. Such machines have not been used for heavier ions, though tests on single modules have recently been made /33,34/.

Although a great deal of technical development is needed before the design of an induction linac to cover the whole range of velocities and pulse length required can be specified, it is clear that the concept represents an attractive approach to a driver for HIF. In the early stages of the accelerator the ions move slowly, and the pulse is long, the current being limited by that which can be drawn from the ion source. During acceleration the bunch length would be progressively shortened, by using a ramped waveform on the gaps to speed up the later particles compared with the earlier ones. At the end of the accelerator the beam would be split and final bunching accomplished during transit throught he beam lines. In order to maintain a small energy spread it is necessary to accelerate the beam gradually, especially at the low energy end. Shaping of the waveform needs to be carefully and accurately done; this can be arranged by having a number of cores in parallel at each gap and triggering them sequentially. Near the ends of the bunch there will be substantial space-charge forces, and these need to be taken into account in specifying the waveform on the gaps. There will be about 10 gaps, so that tolerances on timing needs to be tight if the form of the beam is to be controlled with sufficient accuracy. The role of possible beam instabilities is not yet clear, but no serious problem has been identified. If beam splitting is required to increase the number of beams on target, this could present awkward problems.

Requirements for a 3 MJ driver have been outlined in a 'minimum cost' design by Faltens and Keefe /35/. In order to reduce the problems associated with space charge, especially in the early part of the accelerator, the beam is split into four 'beamlets', each with its own focusing system but sharing the same driving voltage. A total of 6 amps is injected at 3 MeV with pulse duration about 50 μsec. At the end of the accelerator, at the final energy of 10 GeV, the total current is about 3 kA and the pulse duration 100 nsec. Final compression by a factor of about 5 is envisaged in the final beam lines to give the required 20 ns pulse. It may be that many more than four beamlets will turn out to be more favourable, this depends on whether simple focusing arrangements can be worked out /36/. The length of this linac will be several kilometres for singly charged ions.

The use of storage rings is not anticipated, and consequently the number of operations where emittance dilution is likely to be introduced is much less. On the other hand, unlike the situation in conventional linacs, the waveform on every gap has to be carefully tailored. Timing errors on the numerous spark gaps must be kept small. There is special concern about what happens at the end of the bunches, where the space charge forces are large, and the actual velocity distribution that will develop during the acceleration is unknown. The beam dynamics is discussed by Lloyd Smith /37/.

A great deal of technical development, now under way at Berkeley, is required to establish the feasibility of the scheme.

7. FINAL FOCUSING

Although less difficult than the corresponding problem with light ions, the final focusing of heavy ion beams within spots of the required size on the target requires very careful design of the final lens, and a beam with low emittance and small energy spread. In terms of the radius of the target spot r, the lens aperture radius a, and radius of the reactor chamber R, the emittance cannot be smaller then the value required when space charge and aberrations are absent

$$\varepsilon = ra/R \qquad (4)$$

The spot radius r is determined by the target design, (section 3) to be a few millimetres, and R is within the range 5-10 metres for reactor designs considered so far (section 9). The maximum permitted value of a is determined partly by permissible aberration in the lens, but is also strongly influenced by the reactor design. It seems likely to be of order 10 to 30 cm. These figures result in an emittance requirement of tens of mm-mrad. The figure for the original Hiball study was 60 mm-mrad. For a final lens with focal length proportional to ion momentum, the fractional increase in spot size arising from chromatic aberration $\Delta p/p$ is:

$$\Delta r/r = (a/r)(\Delta p/p) \qquad (5)$$

With the figures above this implies a value of $\Delta p/p$ of a few times 10^{-3}. Spherical aberration increases rapidly with a and becomes important for values of a much above 10 cm. An approximate criterion due to Neuffer /38/ for such abberations to be unimportant may be written

$$(a/R)(\rho/r)^{1/4} < 0.15 \qquad (6)$$

where ρ is the radius of curvature of the orbit in the final magnet.

Space charge forces oppose the focusing, and result in a larger spot size than that given by Eq.(4). To account for this Eq.(3) can be generalized to give the approximate relation:

$$\varepsilon = r\left(\frac{a^2}{R^2} - 2K\ln\frac{a}{r}\right)^{\frac{1}{2}} \qquad (7)$$

where K is the beam perveance /39/. For singly charged 10 GeV uranium ions $K \approx 10^{-8} I$, where I is the current in amps. Evidently to keep space charge effects small the second term in the brackets must be kept small compared with the first. When these terms are equal, the equation gives the value of r to which a zero emittance ('laminar') beams of perveance K can be focused. Eq.(7) refers to a beam of uniform density within the cross section; practical beams will be non-uniform, and this introduces aberrations. Numerical calculations for the parameter range appropriate to Hiball shows that these effects are less serious than aberration in the lens /40/.

It is of interest to calculate the two terms in the bracket for typical parameters. Let r = 2.5 mm, a = 15 cm, then for a beam power of 200 TW divided into N beams $K = 2\times10^{-4}/N$, whence $a^2/R^2 = 4\times10^{-4}$ and $2K\ln(a/r) = 16\times10^{-4}/N$. With K = 0, the emittance that could be focused is 50×10^{-6} metre radians; with the full current divided into 8 beams, (N=8), it would be necessary to halve the emittance to enable all the beam to fall within the required spot size.

These simple considerations already indicate the need for a large number of beam lines. Estimates of the emittance to be expected from beams extracted from the storage rings show that this increases with current stored; this again imposes constraints which are probably even more severe. The Hiball design (and proposed modification) has 20 beam lines to each of four reactor vessels.

Until more is known about the characteristics of an induction linac design, it is difficult to anticipate what the beam characteristics (ε and $\Delta p/p$) might be or how many beam lines will be required. Hopefully the smaller number of manipulations required in the overall system will lead to values better than can be obtained from storage rings. It is, however, likely to be a long time before this becomes known.

In the discussion so far it has been assumed that the beam propagates in a vacuum. In the presence of gas at a pressure exceeding a few times 10^{-5} torr in the reactor vessel stripping to higher charge state occurs. At higher pressures a background plasma is created, which can give rise to numerous effects, benign and harmful. These effects are summarized by Olson, with the conclusion that the low pressure regime where stripping and plasma effects are negligible is to be preferred /41/. Nevertheless, it is worth noting the attraction of the alternative pinched beam mode of propagation. This requires a background pressure of order 1 torr, and makes use of a magnetically pinched beam in the plasma which it produces from ionization in the background gas. The beam diameter needs to be kept to below the spot size on the target. This is closely related to the method used for propagating light ion beams, and current limits are such that only a few rather small holes might be needed in the vacuum vessel. Calculations on this mode of transport, whch is also discussed in ref.41 have been made by Buchanan et al /42/.

8. VACUUM CONSIDERATIONS

In conventional accelerators for protons or electrons the operating pressure is determined either by the need to avoid multiple scattering at low energies, or by breakdown on the high voltage gaps which occurs when the pressure is too high. In storage rings, where the particles are contained for much longer, lower pressure is required to avoid multiple scattering on residual gas. Losses arising from mutual scattering of beam particles is, of course, independent of pressure.

For a HIF system additional effects are important. Residual gas also causes stripping of the singly charged ions; for charge states other than unity these ions are excessively deflected in magnetic fields and lost to the chamber walls. At low energies any processes liberating electrons are troublesome since such electrons are drawn into the ion beam, and modify space-charge forces in an unknown way, so that propagation and focusing become pressure dependent. The effect of such electrons dependent. The effect of such electrons depends very much on the local geometrical configuration of the beam and the electric fields surrouning it, it is not easy to estimate. This type of effect is likely to occur early in the accelerator, especially and near the ion source.

A second effect peculiar to heavy ion storage rings is the loss of beam by charge exchange arising from mutual collision of the charges in one of the beams. Loss by stripping can be reduced by lowering the pressure, but there is no way of independently controlling charge exchange loss. The recent emphasis on shorter storage times of the order of 1 ms or less is helpful, nevertheless calculations using expected cross sections indicate that the lifetimes are of the order of 100ms or less, so that about 1% of the beam might get lost /43/.

Stripping cross sections can be estimated, charge exchange cross-sections are more difficult to evaluate, but experimental work has confirmed the order of magnitude expected /44/.

A review of vacuum requirements at the 1977 summer study concluded that loss by ionization and stripping would not be a problem if pressures of 5×10^{-9} torr in the linacs and 10^{-10} in the storage ring could be maintained. These are based on machine parameters now out of date, and the whole question needs re-assessment taking into account revised parameters and improved estimates of cross sections.

Although loss of particles from the beam arising from these processes implies loss of efficiency of the system, far more serious is the possibility of 'runaway' increases in pressure arising from the release of gas or vapour when the beam particles hit the vacuum chamber. Local energy deposition from heavy ions will be much higher than from protons or electrons of the same energy. A potentially serious problems of this type was pointed out by Jones in 1979 /45/, if some of the beam being injected into a storage ring hits the inflector, a burst of gas will be produced; this will interact with the beam to produce stripping and more gas and the process will build up in a catastrophic way. The tolerable loss at injection was estimated to be of order 10^{-4}, but later estimates suggest that this might be greater by a factor 10. This apparently very serious constraint needs careful investigation in the linac and storage ring approach.

A further important area where the vacuum needs careful consideration is the interface between the beam lines and the reactor. This may impose constraints on the reactor design, to be considered next.

9. REACTOR DESIGN

The designs of a reactor vessel for ICF must at the present time be speculative, since there is virtually no experimental experience of the behaviour of materials under the extreme conditions that must be satisfied in an operating power station. Nevertheless, it is very important to make exploratory studies of the various concepts that might be developed, and to do some engineering studies based on the best available data.

Indeed, many such studies have been made since 1971, when ICF first emerged as a serious possibility. These are reviewed in an extensive paper by Monsler et al /46/, and some more recent ideas may be found in the 1982 Livermore Progress report /47/ and a paper by Blink and Monsler /48/. No attempt is made here to review the wide range of factors relevant to reactor design, but some general comments relevant to HIF will be made.

The requirements for lasers, light ion and heavy ions have much in common, though these are some important differences. Their common features is the ability to contain a series of explosions, several per second, each releasing energy of hundreds of megajoules, and pass on the heat generated in suitable form for raising steam for the turbines. Furthermore, the neutrons from the explosions must be absorbed in lithium, and the tritium produced must be extracted to replace that burned in the reactor. The walls must be such as to withstand shock heating and radiation damage without erosion or failure over many years. (This implies about 10^{9} explosions). Entry ports must be provided in the vessel for the beams, and arrangements made to limit the entry neutrons and pellet debris into the beam lines.

Reactor schemes so far studied can be divided into those with dry and wet walls. These are represented respectively by the Westinghouse and Hiball studies /8,9/. In the latter, lithium metal is actually contained within the reaction chamber. This possibility, (not available in magnetic fusion systems), enables protection to be provided to the vulnerable 'first wall' of the reactor vessel. Wet wall schemes, now thought to be the more promising, are discussed further below.

One parameter that reflects the different requirements for different drivers is the base gas pressure in the reaction vessel. As explained in section 1 light ions require 10 to 100 torr, lasers must operate below the gas breakdown limit, about 0.1 torr. Heavy ions on the other hand require a pressure below 10^{-4} torr to avoid stripping. This rather stringent requirement means that pumping must be good enough to restore this only a fraction of a second after the explosion. A further difficulty with wet wall systems is that the vapour pressure of lithium at the temperature required to ensure thermodynamic efficiency is too high /48/. At a pressure of 10^{-4} torr the temperature is only 400°C, at 500°C the pressure is 40 times higher.

This situation can be improved by using instead of pure lithium a eutectic with lead, $Pb_{83}Li_{17}$. This has a vapor pressure of $3x10^{-5}$ torr at 500°C. Additional advantages of this fluid are that in case of accident it does not burn, and also that extra neutrons, available for breeding, are obtained from the n - 2n reaction in lead. Disadvantages are that it is more dense, requiring therefore more pumping power to circulate it, and that polonium is formed as an impurity. This occurs by conversion of Pb 208 to 209 by neutron caputure, beta decay gives Bi 209 which becomes Po 210 by absorbing a further neutron. In addition to this mechanism Bi 208 is a natural impurity in lead. The eutectic $Pb_{83}Li_{17}$ was chosen for the Hiball reactor, and a general discussion of the use of lithium in reactors is given in ref.51.

To make effective use of the lithium or lithium-lead liquid, it must be interposed between the explosion and the chamber wall. Earlier ideas made use of a 'waterfall', or a 'forest' of jets. This latter idea was developed in detail at Livermore into the 'Hylife' concept /49,50/. (High Yield Lithium Injection Fusion Energy converter). In the cylindrical fusion chamber, 5m radius and 8m high, 175 20cm diameter jets of lithium (or lithium-lead) are close packed at radii 0.5 to 1.8 metres. There are of course gaps to allow entry of the beam; the concept was developed originally with two narrow laser beams, adapting it for a large number of particle beams may not be easy.

One problem with this design is that time is taken to re-establish the jets after an explosion, so that pulse rates above about 1-2 per second cannot be achieved. To overcome this difficulty ideas involving lithium in porous flexible environments have been put forward; in Hiball for example the lithium-lead flows through vertical braided porous silicon-carbide tubes. These are packed to a thickness of 2m in front of the 7m radius chamber wall. There are over 3000 tubes of diameter 5cm, and at the inner edge 1200 tubes of diameter 1.5cm. Suitable gaps are arranged for the entry of the 20 beams. The system is designed to operate at 5 cycles per second. The Hiball power station has four such reactor vessels, operating sequentially to give a total pulse rate of 20 per second.

Several alternative design concepts for high pulse rate, using spongy or deeply serrated walls, have recently been proposed /51,52/. Further detailed evaluation is required before their merits and defects can be compared in detail. Indeed, the full evaluation of any reactor concept requires a very considerable amount of detailed work, both on engineering layout of the components, and a study of the physics and hydrodynamics of the explosion, both of which depend of the target design and chamber pressure.

There is always likely to be a conflict of interests between accelerator and reactor designers at the interface between the beam lines and reactor vessel. Accelerator designers would like many apertures of fair size so that focusing to a small enough spot is possible; reactor designers regard such apertures as an unwelcome perturbation and would like them to be few and small. It is to be hoped that a satisfactory compromise can ultimately be found.

10. FUTURE OUTLOOK

It has long been appreciated that a development strategy for HIF presents special difficulties. Scaling laws do not allow the 'scaled down' approach which has been followed with lasers, and the structure of the overall installation does not permit the 'modular approach' suitable for light ions. The setting of intermediate objectives whose attainment really gives confidence in the concept without being too costly is therefore difficult. Serious efforts are now being made to define 'high temperature' experiments, that will produce sufficient concentration of energy in a target that a plasma with an 'interesting' temperature (50-100 eV) is formed and at the same time address the problems to be faced in accelerator system, particularly those arising from space charge effects, which cannot be treated analytically. It is clearly profitable also to investigate individual specific problems, as has been done for example in the case of charge exchange cross sections.

A proper balance must be kept between detailed activity, and evaluation of the whole concept. It is particularly important for the credibility of the enterprise to be able to point to a complete power station scenario, consisting of target, accelerator, and reactor, that is consistent within the bounds of our present understanding. To achieve this requires particular attention to be paid to the three interfaces between target, accelerator, and reactor. (Limitations in one's own domain are more clearly perceived than those faced by a neighbour!) A recurring example of an interface problem is that between accelerator and reactor. How many beams are permitted, and what is the size of the apertures in the chamber wall? It is important that proper attention be given to these overall scenarios, and that they are not forgotten during the detailed work on particular problems.

Seven years have passed since the first wave of excitement about HIF rippled through the accelerator community gathered at the Claremont Hotel in Berkeley. This was followed by a period which, despite positive progress, was characterised by much confusion, frustration, and agony; now the issues seem clearer, and the road to a systematic evaluation of this far reaching and ambitious enterprise is being planned. Who knows what the next seven years will bring?

11 - ACKNOWLEDGEMENTS

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