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HEAVY ION INERTIAL FUSION

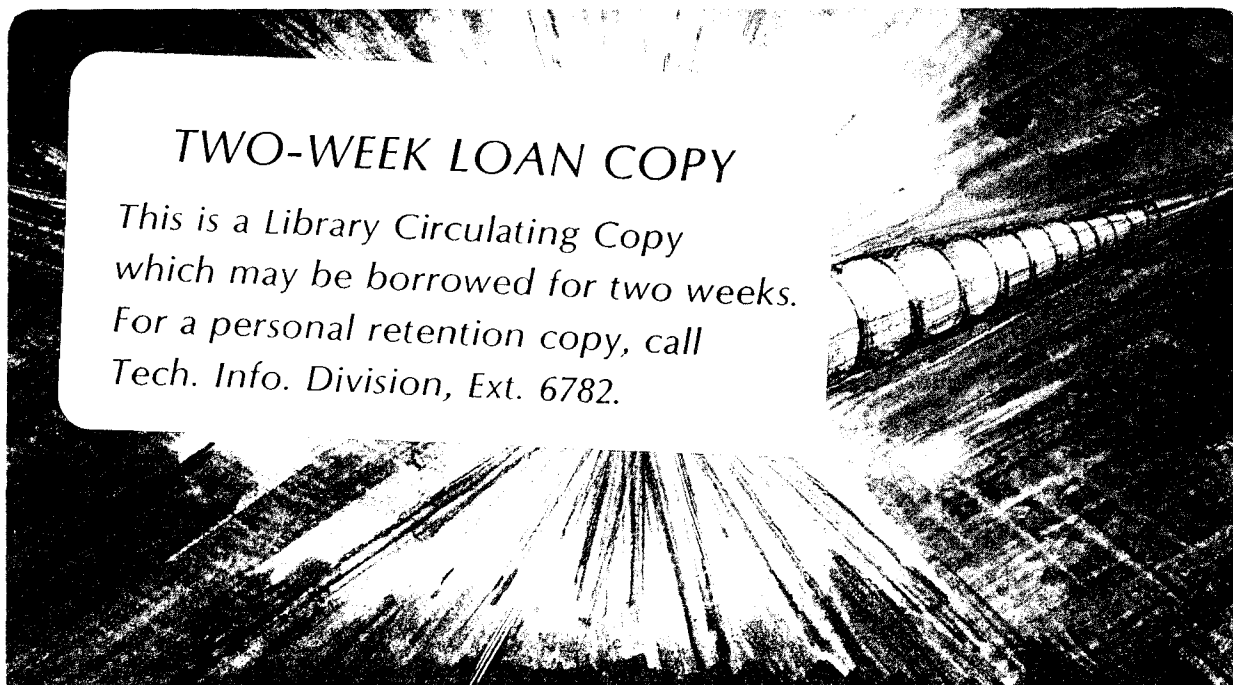
D. Keefe and A.M. Sessler

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## HEAVY ION INERTIAL FUSION<sup>\*)</sup>

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### ABSTRACT

Inertial fusion has not yet been as well explored as magnetic fusion but can offer certain advantages as an alternative source of electric energy for the future. Present experiments use high-power beams from lasers and light-ion diodes to compress the deuterium-tritium (D-T) pellets but these will probably be unsuitable for a power plant. A more promising method is to use intense heavy-ion beams from accelerator systems similar to those used for nuclear and high-energy physics; the present paper addresses itself to this alternative. As will be demonstrated the very high beam power needed poses new design questions, from the ion source through the accelerating system, the beam transport system, to the final focus. These problems will require extensive study, both theoretically and experimentally, over the next several years before an optimum design for an inertial fusion driver can be arrived at.

### 1. Introduction:

For thermonuclear fusion to work as a practical source of electricity, physics requires that two conditions be achieved simultaneously for a deuterium-tritium mixture:

- the hot plasma must be adequately confined; that is, the product of number-density times the confinement time ( $= n\tau$ ) should lie close to  $10^{15}$  sec.  $\text{cm}^{-3}$  (Lawson Criterion);
- the temperature should be in the region of 20 keV.

An interesting milestone along the road to useful energy is "scientific-breakeven" wherein the burning fuel liberates energy in an amount equal to that provided directly to the plasma. (This is still a long way from "engineering-breakeven" in which the released energy equals the total energy needed for the whole system and, of course, still farther from useful net energy production). Scientific breakeven can be achieved for an ( $n\tau$ ) product an order of magnitude less and a temperature a factor of two less than the values above. For tokamaks each of these goals has been met in separate devices, the first in Alcator at MIT and the second in the Princeton Large Torus. Both are expected to occur simultaneously and provide break-even in the Tokamak Fusion Test Reactor which will be completed in 1982 at Princeton; this is to have a confinement time of the order of one second and a repetition rate somewhat less than one per hour.

Financial support for inertial fusion has hitherto been substantially less than for magnetic fusion and progress to date correspondingly less. If, indeed, the concept of compressing and heating small pellets of D-T to achieve high gain (ratio of energy released to energy delivered to pellet) is found to be successful then the promise of useful energy from inertial fusion relative to magnetic fusion could be enhanced. This is chiefly for two reasons. First, the containment vessel -- which in either case must handle the high wall loading and the neutron flux -- allows of much more flexibility in design, scale and shape, and choice of materials, than does that in a tokamak where it

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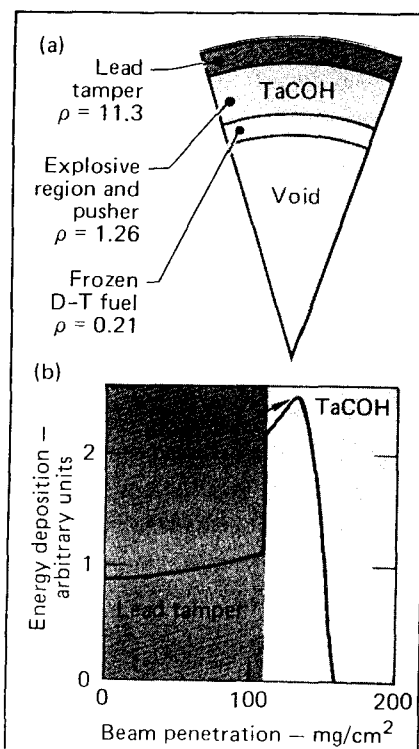
\*) Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48.

must be embedded in the nested toroidal and vertical field-coils and operate in a high magnetic field. The second reason is the appreciation -- following the initial suggestion by Maschke and by Martin and Arnold in 1974 -- that not alone would an intense beam of heavy ions provide a particularly suitable way of imploding pellets, but that we could capitalize on the several decades of ideas and developments in the accelerator field and so by-pass the many hard years of engineering development that were perceived to lie between "scientific-breakeven" and a working power-plant. How true this is depends on the extent of the extrapolation from present practice.

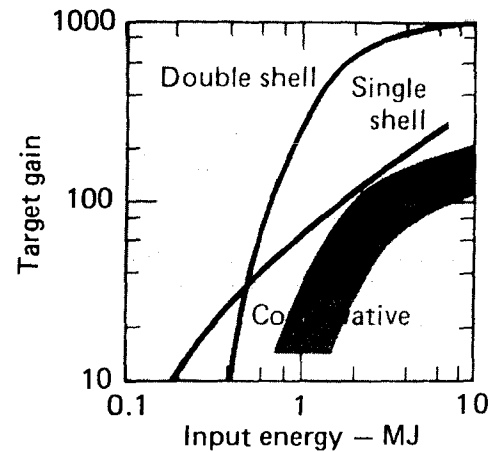
## 2. Inertial Confinement Fusion

While for inertial fusion to work the two conditions given earlier need to be met, the scale of some of the individual parameters are dramatically different than those common in either magnetic fusion or accelerator physics. Typical pellet sizes needed will be on the order of a milligram in mass (one milligram of D-T with 100 percent fusion releases 350 MJ) and on the order of a millimeter in radius. If one were simply to heat such a pellet suddenly to 20 keV it would remain inertially contained for a time of 1-nsec (pellet dimension/ion thermal speed =  $2 \times 10^6$  m/sec) before it disassembled. Since the number density of solid D-T is  $5 \times 10^{22}$  cm<sup>-3</sup> the  $n\tau$  product would be  $5 \times 10^{13}$  and fail to meet the Lawson criterion for fusion power. In addition, at this number-density the pellet is transparent to the  $\alpha$ -particles produced as reaction products so that they escape. A radial compression, prior to heating, by a factor of ten dramatically alters matters; the time is shortened by a factor of one-tenth (radius ratio) but the number density increases by a factor of one thousand; thus ( $n\tau$ ) goes up one hundred times and the Lawson criterion is comfortably reached. Furthermore, as a result of the reaction  $D + T \rightarrow \alpha + n + 17.6$  MeV, the  $\alpha$ -particle range, which is inversely proportional to  $n$ , is short enough that the  $\alpha$ -particle stops in the fuel and the energy deposited leads to the so-called "ignition" condition. Most of the neutrons, however, will still escape and convey their energy to the reactor walls.

To arrange for a volume compression ratio of  $10^3$  the fuel is surrounded by concentric shells of chosen materials and energy from the driver is supplied rapidly to the outermost surface. If laser light is used, a common design employs the ablative or "rocket" action; the light heats the outer surface which becomes a plasma and the recoil momentum from the outward-flying ions drives the interior shells inwards. For ion-beams such targets can work but alternatives such as a "cannon" scheme are possible. If the surface layer is a thin shell, made of lead, the ions can penetrate it and deposit most of their energy in a low-density underlying shell. Expansion of the low-density plasma is inhibited on the outside by the inertia of the heavy shell which acts as a



tamper and so the interior fuel is imploded. More complicated geometries are possible, for example, a double-shell design in which an outer shell is driven steadily inwards to collide with and transfer its momentum to a second shell which thus is rapidly imploded. There are more uncertainties in the performance of double-shell targets because of susceptibility to hydrodynamical instabilities but they do offer the prospect of reaching very high gains, perhaps 1000. The sketch shows the expected gain as a function of input energy for single and double shell targets; also shown is a "conservative" band which might correspond to the real situation if several of the experimental uncertainties were to combine in an unfavorable way. Thus, for example, to achieve a gain of 100 it would be prudent to assume that an input energy between 2 and 8 MJ would be needed.



### 3. Drivers

Three systems under consideration for supplying the needed energy are lasers, light-ion accelerators and heavy-ion accelerators. It is important to distinguish between the use of any system for research on the physics of the pellet behavior and its ultimate promise for a realistic power-plant application. (See Table 1). For instance, the largest laser system operating today is the 20 kJ SHIVA neodymium-glass laser at Livermore which has already achieved fuel compression to some 50 times liquid density. (It will be replaced a few years from now by the NOVA system with about an order of magnitude increase in energy). Because of its extremely low repetition rate and low efficiency a glass laser is not a candidate for a power plant driver. Both these features can be circumvented to some degree with gas lasers but the unfavorable laser-plasma interactions of long wave-length (10  $\mu\text{m}$ ) light make the  $\text{CO}_2$  laser seem unsuitable and the preferred short wavelength (0.25  $\mu\text{m}$ ) KrF laser is still only in an early state of development. Also the maximum wall-plug efficiency for the KrF laser is projected to be about 6 percent.

TABLE 1: Driver Requirements for Power Production

- Energy - 1 to 10 MJ
- Power - 100 to 600 TW
- Pulse shape - Control needed
- Efficiency x gain > 10
- Focusing - to a few mm at 5 to 10 m
- Reliability - > 80% on time
- Lifetime - 30 year
- Rep rate - 1 to 10/sec
- Cost - (a few)  $\times 10^8$  \$/GW of electrical output

The importance of efficiency is easy to see. To produce a pulse energy,  $Q$ , a driver with efficiency,  $\eta$ , requires an input energy  $Q/\eta$ . The burning of a pellet with gain,  $G$ ,

leads to an output electrical energy,  $QG/3$ , where the thermo-electric conversion efficiency has been taken to be  $1/3$ . If we specify that the recirculated power fraction consumed by the driver (which is only one part of the power plant) be small then we must have

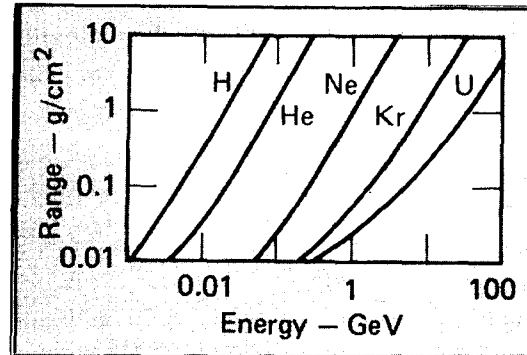
$$nG \gg 3, \text{ or, say, } nG \geq 10.$$

If the pellet physics turns out to limit one to  $G = 100$  then a driver is an interesting candidate only if its efficiency exceeds 10 percent.

Light- and heavy-ion drivers can comfortably meet this condition. Also the volumetric nature of their energy deposition rather than the surface deposition of laser light is viewed as a distinct advantage. It can be easily seen how ion-drivers can supply megajoules of beam energy but the short-pulse length ( $\approx 20$  nsec) implied by the needed high power (c.f. Table 1) poses special problems. For lasers the situation is the opposite -- they are poor in energy but rich in power.

A typical set of parameters appropriate for a heavy-ion driver is given in Table 2. (While uranium is frequently used as an example for deriving numbers it should not be considered the best choice of nuclear species but only as a surrogate for high-mass ions with  $A > 200$ .) A driver with these properties would need to operate at a repetition rate of 10 Hz if the electrical power output were to be in the 1 GWe range.

Since the pellet-designers specify the ion range to be  $0.2 \text{ gm/cm}^2$  (or less) a quick comparison with the needs for a light-ion (usually proton) driver can be seen by reference to the range-energy curves. Instead of the 10 GeV needed for heavy ions the proton energy should be about 7 MeV, which corresponds to a final proton beam current needed of a formidable 20 megamperes. It is known how to achieve such a total current by an array of several dozen pulse-power ion diodes and,



indeed, experiments are expected to begin next year at Sandia Albuquerque with the PBFA I which will have 15 MA, 2 MV protons, 1.2 MJ and 30 TW. Three major questions arise, however, about the conceivable utility of this approach for future power plant application. First, pulse-power devices of this kind are strictly for one-shot operation and progress towards reasonable repetition rate will probably require a major re-vamping of the technology, probably towards more distributed systems of much smaller energy packages such as, for example, are used in induction-linac technology. Second, strong plasma effects -- such as channels produced by exploding wires strung between the diodes and the target -- must be relied on to transport the large currents; how well these will work is not known. Finally, the distance between the diodes and target may have to be short, in which case a large energy release from the pellet would seriously damage the driver in a single shot. A credible reactor scenario, therefore, is hard to conceive of at this time.

Table 2: TYPICAL PARAMETERS FOR A "URANIUM"-BEAM  
POWER PLANT DRIVER

Beam energy = 3 MJ/pulse
Ion kinetic energy = 10 GeV
Ion Range in hot plasma = $0.2 \text{ gm/cm}^2$
Beam charge = 300 particle $\mu\text{C}$
Number of ions = $2 \times 10^{15}$
Pulse length needed at pellet = 20 nsec
Power at pellet = 150 TW
Beam current at pellet = 15 kA
Beam spot radius at pellet = 2.5 mm
Specific energy deposition in pellet = 40 MJ/gm
Energy released (for G = 100) = 300 MJ (or about 1 mg of fuel consumed)/pulse

Nonetheless, these light-ion devices offer an extremely interesting experimental tool to learn about the pellet physics at a cost per joule significantly less than that from either a laser or a heavy-ion accelerator. Such experiments have a particular interest for advocates of heavy ions since they will provide valuable information about intense energy deposition by ions in hot plasma and, further, will be pushing to explore alternative pellet designs that might need much lower beam-power.

#### 4. Constraints imposed by Reactor on the Heavy-Ion Beam

Wall-loading considerations require the reactor vessel to be about 5 to 10 meters in radius. Dry-wall designs (e.g. pyrolytic graphite) may have a lifetime shorter than the plant life of 30 years and would need to be replaced several times. A number of wet wall concepts (e.g. liquid lithium waterfalls or jets or, alternatively, a lithium-lead eutectic) would provide blast and neutron protection and additionally allow in situ breeding of tritium from the neutron-lithium reaction. The heavy ions enter the reactor as two bundles of beamlets from opposite sides, each bundle containing some 5 - 10 beamlets. An acceptable engineering solution is to arrange for the background pressure to be in the  $10^{-4}$  -  $10^{-3}$  Torr range or less. In that case the ion beams propagate ballistically as in high vacuum. It is still uncertain whether the reactor can also be operated with a poor vacuum ( $\sim 1$  Torr) and still allow the ion-beams to propagate across the chamber without disruptive plasma effects.

The optics of the final beam quadrupole lenses demands that the angular divergence of each beamlet be kept less than about 20 mrad to avoid significant spherical aberration. (This aberration could be corrected to some degree by octupoles and this requirement eased somewhat.) Using  $\beta = 0.29$  for the ions and a pellet radius of 2.5 mm, we conclude that the normalized emittance per beamlet should be no larger than  $1.7 \pi \text{ cm-mrad}$ . Note that if the beamlets are created by splitting in transverse phase-space the emittance in the accelerated beam can, of course, be larger. Considerations of chromatic aberration -- which in turn can be reduced by sextupoles -- during the final focussing lead to a constraint that  $(\Delta p/p)_{\text{final}} < 1.5$  percent. As the bunched beam strikes the pellet it is only 2 meters in length. Considerations of longitudinal phase space require that the

momentum spread in the accelerator must be maintained at a very much smaller value since the beam will be vastly longer during acceleration.

## 5. Accelerator Performance Criteria

So far we have discussed the beam needs set by the pellet and reactor designers. The next questions are: What accelerator tools can do the job? and, Can the known design constraints set by the accelerator physics permit us to arrive at an economic and efficient solution? Parenthetically, it should be noted that the task has become harder since the first large workshop on the subject was held at the Claremont Hotel, Berkeley, in 1976. At that time it was believed that 1 MJ of 100 GeV ions would be suitable; since then the energy requirement has moved up to 3 MJ and, more serious, the kinetic energy has been reduced by an order of magnitude.

The central problem is achieving the high beam power which, as discovered by Maschke, is limited by the transport system and scales as  $(\gamma - 1)(\beta\gamma)^{5/3}$ . Non-relativistically this is a scaling slightly less than  $(\text{kinetic energy})^2$  and relativistically almost as  $(\text{kinetic energy})^3$ . While we have experience with multi-megajoule proton accelerators at FNAL and CERN they are in the ultra-relativistic range and still only barely in the 1 TW class! The decrease in desired ion-energy from 100 GeV to 10 GeV has thus significantly aggravated the problem.

Nonetheless, there seem to be two solutions each with promise of success. One uses an rf linac to accelerate about 100 mA to full energy. The early part of the linac will need parallel low-frequency low-beta linacs arranged in a funnel fashion (see Sect. 6) and will involve frequency jumps with longitudinal phase-space matching to preserve the longitudinal emittance. At full energy the beam is transferred to storage rings (10-20 in number) via an intermediate stacking ring to allow multi-turn stacking in both vertical and horizontal phase planes. The current is increased further by strong bunching and delivered in multiple beams to the pellet. The other scheme is a single-pass induction linac in which current amplification takes place continuously during acceleration (see Sec. 6). The injection current is several amperes (one hundred times that in the rf linac) and the entire beam is accelerated in a single long sausage-like bunch. Early on, the voltage pulses to the induction cores are ramped slightly upwards with time thus differentially accelerating the tail of the bunch with respect to the head. As the velocity is increased and the bunch length decreased the beam current rises to about 2 kA at the end of acceleration. A strongly-ramped voltage is applied to initiate a strong longitudinal compression which takes place in the transport system to the target. As the current rises sharply the beam must be split by transverse septa so that the current per transport line does not exceed some 1 kA, except perhaps briefly.

We can briefly summarize as follows the current views on the accelerator systems under study:

-- Ion sources for either rf ( $\sim 1/10$  amp) or induction linacs ( $\sim 5 - 10$  A) are not a problem. High-current  $\text{Xe}^{+1}$  sources for an rf linac have now been operated successfully at ANL, BNL, and LBL with satisfactory emittance in the range 30 - 60



mA. The ANL source was developed by Hughes Research Laboratories and derives from designs for ion propulsion sources. The LBL multiaperture source is directly scaled from our neutral beam sources which deliver more than 50 amps of protons. Large-area contact ionization sources for  $\text{Cs}^{+1}$  have been demonstrated to give 1 amp at LBL. Such sources can give the several amperes needed for injection into an induction linac. We have also demonstrated suitably large pulsed currents of  $\text{Cs}^{+1}$  and  $\text{Tl}^{+1}$  from heated aluminasilicate sources.

-- rf linacs for heavy ions exist for nuclear physics research (e.g. SuperHILAC, Unilac). Extension of the design to much higher current and smaller charge/mass ratio -- and lower velocity -- is in progress at ANL and BNL.

-- Induction linacs have been widely used for electron beams in the 1 kA current range and manipulations such as controlled ramping of the beam energy demonstrated. Extension to slow particles has not yet been achieved but should not present real problems.

-- The synchrotron's advantage as a research tool to provide very high kinetic energy for low capital cost is seriously undermined for this application. The very high injection energy needed to achieve a high space charge limit and the very low peak energy (10 GeV ~ 50 MeV/amu) are unfavorable. Also, the extra manipulations introduced by adding a synchrotron (injection, extraction, de- and re-bunching) and the need to cycle it rapidly to avoid beam loss from intra-beam charge exchange reactions make it less attractive.

-- The storage rings needed for current amplification with the rf system have some problems in common with those that will be needed for e-p colliding beams but must deal with still higher currents. Stacking simultaneously in both transverse planes is needed and the storage time must be short (a few milliseconds) to avoid significant beam loss from ion-ion charge exchange.

-- Because of the high energy-density and short range of the ions, manipulations involving septa, e.g. injection and extraction for storage rings, transverse splitting for the induction linac, require special attention. A small amount of beam loss on an injection septum in a storage ring can lead to vaporization and production of a gas cloud that will impede succeeding portions of the beam. For septum splitting of the induction linac beam the beam dimension needs to be increased by a factor of five if one wishes to avoid spalling of the front edge of the septum magnet.

-- Both the rf linac/storage ring and induction linac schemes involve new techniques of beam manipulation which, while mostly credible conceptually, have not been achieved in practice. The number of manipulations is fewer in the single-pass induction linac than in the storage ring scheme since in the latter the current amplification ratio has to be greater by a factor of one hundred.

Next we briefly review the likely limiting phenomena which are all due to plasma (self-field) effects. Transverse effects limit the current or lead to emittance increase; longitudinal effects lead to an increase in  $\Delta p/p$  or to beam loss. It is

believed that coupling between these degrees of freedom may play an important role because of the high value of the beam plasma frequency compared with the betatron frequency. Attempts are being made to address this coupling by means of a fluid model; ultimately the need for 3-D simulation is foreseen. The limitations we do know specifically and must design around are as follows:

(i) In the storage rings the Laslett tune-shift condition applies for transverse stability, i.e., the number, N, of stored particles is constrained by

$$N < \frac{2\pi \Delta\nu}{b r_p} \left( \frac{M}{M_p} \right) \left( \frac{1}{q^2} \right) \epsilon_N \beta \gamma^2 \quad (1)$$

where  $b$  = bunching factor  
 $r_p$  = classical radius of proton =  $1.5 \times 10^{-16}$  cm  
 $q$  = ionization state of stored ions  
 $\pi\epsilon_N$  = normalized transverse emittance

For quasi-steady storage conditions  $\Delta\nu$  has the value 0.25. In the final rapid bunching needed just before extraction this value can be exceeded for a transient situation; a bunching experiment by Maschke at the A.G.S. demonstrated that by rapidly passing through the resonances  $\Delta\nu \approx 2$  could be attained. For a heavy ion driver  $\beta \approx 0.3$ ,  $\gamma \approx 1$  and the emittance  $\epsilon_N$  must be kept small thus the requirements set by Eq. 1 demand that some 10 to 20 storage rings are needed. Also, it is undesirable to use an ion with a charge-state of much greater than unity.

(ii) The longitudinal resistive limit for the storage rings is low enough that one is always well above threshold since the momentum spread is too small to provide adequate Landau damping. Thus successful operation requires that the growth time, T, be adequately long, where

$$\frac{1}{T} = n\omega \frac{(R_n/n)}{2(X_n/n)^{1/2}} \left( \frac{\ln |I_{qe}|}{2\pi\beta^2 \gamma M c^2} \right)^{1/2} \quad (2)$$

where  $n$  = mode number  
 $\omega$  = revolution angular frequency  
 $n = (1/\gamma_{trans}^2) - 1/\gamma^2$   
 $Z_n = R_n + iX_n$  = structure impedance

Growth times can be of the order of a millisecond if the structure resistance can be kept to a value of  $R_n/n < 2$  ohms which is somewhat better than the values in the PS and ISR.

(iii) For linear beam transport systems the maximum current, and hence power, that can be transported in a quadrupole lattice is limited by the maximum attainable focussing, as first pointed out by Maschke. Extensive computational work by Laslett and Smith who use a K-V distribution have verified this in detail. Their results are confirmed by numerical simulation by Haber. The corresponding space-charge depression of the phase-advance/period in a FODO lattice is from  $60^\circ$  to  $24^\circ$ . The limiting power is

$$P(\text{watts}) = (1.7 \times 10^{15}) \left( \frac{M}{M_p} \frac{1}{q} \right)^{4/3} (\epsilon_N B)^{2/3} (\beta\gamma)^{5/3} (\gamma - 1) \quad (3)$$

where  $B$  = quadrupole "pole-tip" field averaged along transport line (teslas)  
 $\epsilon_N$  = normalized emittance (meter radians)

The subdivision of the final beam transport into 10-20 beamlets finally on target allows this condition to be obeyed provided high-field superconducting quadrupoles are used.

A corresponding space charge limiting current can be derived from Eq. 3 by dividing by the beam voltage,  $Mc^2(\gamma-1)/q$ , and this limit is of crucial importance to the induction linac design. For a voltage increment,  $\Delta V$ , the energy supplied to the beam is  $(I)\Delta V$ , where  $(I)$  is the beam charge. The higher  $I$  can be at that point the fewer volt-seconds of core ( $\Delta V$ ) will be needed for the same energy increment and this would be reflected in lower cost. For distribution functions more realistic than the K-V distribution the numerical simulation results suggest that the coefficient in Eq. 3 is too small but probably it is not wrong by as much as a factor of two.

(iv) The longitudinal resistive instability is not a problem for the r-f linac but must be considered in detail for the induction linac where the current is typically 10,000 times greater. Since we are dealing with a single bunch the theory is incomplete. Simple theory suggests that the fast plasma wave decays while the slow wave grows as it travels to the back of the bunch but then is reflected into a forward-going decaying wave. A one-dimensional numerical simulation code at LBL shows more complicated behavior at the bunch end but the results are not yet comprehensive enough to be sure that these are real effects or computer artifacts.

If we take  $X_n/n = Z_0(1 + 2 \ln b/a)/\beta\gamma^2$  then, for an infinitely long bunch, the growth length,  $\lambda$ , is given by

$$\frac{1}{\lambda} = \frac{R'}{Z_0} \left( \frac{4\pi^2 q^2}{(1 + 2 \ln b/a)} \cdot \frac{M_p}{M} \cdot \frac{N}{L} r_p \right)^{1/2} \quad (4)$$

where  $R'$  = real part of impedance/meter  
 $b/a$  = pipe radius/beam radius  $\approx 1$   
 $Z_0$  = free-space impedance = 377 ohms  
 $N/L$  = line density of ions

For an induction linac  $R'$  is small for high frequencies and very low frequency troubles can be cured by feed-forward if need be. Using a worst case  $R' \sim 100$  ohm/meter,  $\lambda \approx 1$  km. Numerical simulation shows growth times of this order although whether the effects are self-healing or not in the bunched case is still unclear.

## 6. Conceptual Design of Drivers

The application of the above limiting considerations together with judgments from experimental experience with other machines to the conceptual design of driver systems has been quite well documented in the proceedings of the four annual workshops held on

the subject (1976-79). Examples of so-called "Reference Designs" discussed at the 1978 workshop at ANL are shown in Figs. 1 and 2. The rf/storage ring design differs only in detail from an earlier 10 MJ driver design described by Maschke.

Both designs are still conceptually current but need detailed up-dating to respond to the recent changes in the target-designers wishes, i.e., a beam-energy increase from 1 MJ to 3 MJ, and a kinetic energy decrease from 20 GeV to 10 GeV. In partial compensation, however, the final pulse-length needed at the target has been relaxed by a factor of three so that the beam power remains the same. At the most recent workshop (Claremont, 1979) a charge state as high as  $q = 8$  was considered dangerously large because of longitudinal limits in the rings, and the rf design will probably end up with  $q = 1$  or 2. For other reasons, the induction linac will probably also use  $q = 1$  or 2. (At least for the induction linac, the cost has been shown to be only weakly dependent on charge-state). The major change expected because of the increased beam charge is amplification of the low- $\beta$  injector sections and in the details of the storing and/or splitting of the final beam lines. In the induction linac it may be necessary to use more than one pulsed injector or, better, to accelerate several discrete beams within the same drift-tube structure along the lines proposed by Herrmannsfeldt and by Maschke.

#### 7. Present Experimental Programs

Relative to the scale of research and development that will be needed eventually to construct a working heavy-ion driver, the experimental activities at Argonne, Berkeley and Brookhaven can, at best, be described as extremely modest. Present activities center about the questions of handling the high-current low- $\beta$  end of both systems with special attention to preservation of low emittance. Experimental studies on the question of high-current stability in storage rings and long induction linacs must await the future.

At ANL, the Hughes source has been successfully operated at 40 mA of  $Xe^{+1}$  at 1 MV supplied by a dynamitron. It is intended in the short term to test the funnel-loading concept by accelerating through a 12.5 MHz Wideroe to 9 MeV, deflect transversely, go through a longitudinal phase-space matching section, and resume acceleration in a 25 MHz Wideroe. Understanding of emittance growth and beam loss in the first Wideroe and during manipulations to transfer to the second Wideroe is a crucial goal. At this time the buncher and the first of three independently-phased cavities have been operated with good results; the first Wideroe is under construction (Fig. 3). Later it is planned to strip to  $Xe^{+8}$  at the end of the second Wideroe, accelerate to 220 MeV and inject into a large-aperture synchrotron which could provide about a kilojoule of  $Xe^{+8}$  ions at 10 GeV.

At BNL a duoplasmatron  $Xe^{+1}$  source has been operated with a Cockcroft-Walton and beam accelerated through a 16 MHz multi-drift-tube Wideroe linac. Lately, however, Maschke and coworkers have been investigating a method of transporting high currents at low  $\beta$  by means of an array of small beamlets focussed by close-packed electrostatic quadrupoles. Usually the beam current is limited not by the emission of the source but by the transport system and the deep potential well within the beam. One can improve matters by sub-dividing the beams into ribbons and use an einzel-lens method of focussing (Herrmannsfeldt) or use parallel quadrupole channels (Maschke). From Eq. 3 we note that

the total current transported in  $n$  beams each of emittance  $\epsilon_N/\sqrt{n}$  exceeds that transportable in one beam by a factor  $n^{2/3}$ . Tests have been made for  $\text{Xe}^{+1}$  with  $n = 9$ ; also a 50 MHz rf proton linac from 20 kV to 100 kV which uses four parallel quadrupole systems in the drift tubes has been completed and will soon be extended to 750 kV.

At LBL, apart from an early demonstration of a 50 mA  $\text{Xe}^{+1}$  beam at 500 kV, suitable for an rf linac, based on the CTR source design, experimental work has been devoted to the induction linac technology. A cesium contact-ionization source is in routine operation; it has delivered 1.2 A at 500 kV for 2  $\mu\text{sec}$  pulsed at a 1 Hz rate. A system of three drift-tubes each of which will be pulsed (2  $\mu\text{sec}$ ) to 500 keV is now operational (Fig. 4). The system has just been tested at half-voltage and the beam-optics confirmed to agree with the simulation calculations by Herrmannsfeldt's code. Experiments on sub-dividing the beam into individually-focussed beamlets are planned for the future.

The features critical to the induction linac scenario include being able to inject a long sausage-like bunch into an induction linac and show that the manipulations which lead to current amplification can be handled in a controlled way without excessive degradation of the 6-D emittance. To this end a 10 MeV  $\text{Cs}^+$  "test-bed" (Fig. 5) has been designed and we would expect to achieve a current amplification from 1 A to 3A in a length of 80 m. A single-particle computer simulation has been used to derive the needed voltage-pulse profiles and an engineering prototyping effort is underway to arrive at realistic designs to achieve these shapes.

#### REFERENCES

Details of the work discussed here can be found in:

- Proc. ERDA Summer Study of Heavy Ions for Inertial Fusion, (Berkeley 1976) LBL-5543
- Proc. Heavy Ion Fusion Workshop (Brookhaven 1977) BNL-50769
- Proc. Heavy Ion Fusion Workshop (Argonne 1978) ANL-79-41
- Proc. Workshop on High Current Phenomena (Berkeley 1979) to be published.

Recent comprehensive reviews include:

- Assessment of Drivers and Reactors for Inertial Confinement Fusion, K.A. Brueckner (ed.) EPRI AP-1371 (1980)
- The Development of Heavy-Ion Accelerators as Drivers for Inertially Confined Fusion, W.B. Herrmannsfeldt, LBL-9332/SLAC-221 (1979)
- Fusion Driven by Heavy Ion Beams, A. Pascolini and M. Pusterla, Univ. di Padova IFPD 11/80 (1980)