INERTIAL FUSION WITH LOW ENERGY HEAVY IONS*

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High energy heavy ions have been under study for inertial fusion applications for some time.¹ The purpose of this note is to point out that it may be possible to utilize heavy ions with energies less than 1 MeV, compared with the usual HIF approach using multi-GeV beams.

The basic idea is to produce the heavy ion beams in a spherically focused array, using time-of-flight bunching.^{2,3,4} The key to producing high power density at the target is to be able to accelerate a sufficiently bright beam to the required energies. The MEQALAC (Multipole Electrostatic Quadrupole Array Linear Accelerator) concept allows one to accelerate high current beams, of any current density which can be extracted from an ion source, to arbitrarily high voltages. For beams in this energy range, the MEQALAC could be powered directly with a "D.C." potential, or by a pulsed drift tube MEQALAC, or an induction MEQALAC.

Because the time-of-flight bunching restricts the length of the pulse, one can write down an expression for the maximum energy in a single pulse. One obtains $E_{\max} = 4.55 \times 10^{-4} \times J(VA)^{1/2} R^3$. If we take some plausible number for a fusion reactor, one might have $E_{\max} = 1$ MJ, $R = 10$ meters, $V = 10^6$ and $A = 200$. Then the requirement on the average current density would become $J = 155$ amps/m². Of course, current density is not the whole story. The beam will need to have a low transverse temperature in order to be focused to an appropriately sized spot. Typically, 1 mr would be nice, corresponding to a transverse temperature of 1 eV, and a spot of 1 cm radius. A word on the final spot size is in order here. The final convergence density could be computed from consideration of six-dimensional phase space invariance for a non-interacting beam. However, as the beam interacts with the target it may actually acquire substantially higher densities. This is due in part to the fact that the beam has done work on the target material and, also, because the heavy ions radiate so much that radiation cooling actually improves the convergence.

For the example parameter taken above, the mass of the beam turns out to be ~ 2 mg. This is substantially greater than the fuel mass that would typically be associated with a 1 MJ pellet. Therefore, the momentum of the beam can play a significant role in the implosion process. The condition that this be the case is that the momentum transfer between beam and target take place such that the range of the target particle be small compared with the beam thickness. In other words, the "rho-r" for momentum transfer to a target ion should be less than or equal to the "rho-r" of the beam. This puts a limit on the energy that the beam can have and still be considered momentum rich. We obtain $v_{\max} \propto Z_{\text{eff}}^{4/3} A^{5/3}$. For our parameters we would have $Z_{\text{eff}} \sim 10-20$. $v_{\max}$ would

probably be $\sim$ several MV. However, if light ions were used, this restriction would occur at a voltage of a few hundred volts.

A distinctly novel feature of low energy heavy ions, as compared with conventional heavy ion fusion (or light ion fusion for that matter), is that the ion velocity is slow compared with either background plasma electron velocities, or orbital electron velocities. The former suggests freedom from electrostatic plasma instabilities⁶ during transport. The latter allows one to make use of the large resonant charge exchange cross section to produce a neutral atom beam with negligible scattering.

The ion source requirements for these beams are unique, in the sense that there has not previously been any demand for pulsed ($\sim 1-10$ microseconds) high current, high density heavy ion beams. A number of novel approaches look attractive. Zeolite sources, under pulsed conditions can give high current densities.⁷ Also photodissociation of thallium halides has been suggested by P. Davidovits as a possible source of cold dense heavy ions.⁸ Work done at TRW indicates that existing ion sources may be capable of extracting over 1 amp/cm² of xenon.⁹ M. Dembinski and P.K. Jahn** have suggested using a flowing plasma to allow one to extract high current densities of very bright beams.¹⁰ Although their experiment was done with hydrogen, the principle should be generally applicable for any ion.

If the beam of our example is compressed in time by a factor of 1000, then the power on target is nearly 200 TW, which is in the ballpark where one expects to be able to produce inertial fusion. At the present time, there is a need for more computer simulations¹¹ to try to find out in detail what is required. It should be noted that if one attempts to achieve the maximum power at the smallest spot size, the six-dimensional phase space invariant would limit one to ~ 7 TW. (This is the equivalent of an adiabatic compression of the beam.) However, in typical cases, the beam compression is very non-adiabatic. For instance, even for a case where we have an "empty target", the beam will self-interact and radiate strongly. The entire subsequent implosion of the beam becomes dominated by considerations of radiation transport and losses.

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