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PELLET FUSION BY HIGH ENERGY HEAVY IONS*

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Introduction

Initial ideas on fusion based on conventional high energy accelerator technology were presented two year ago.[1-2] Concepts at Argonne evolved from protons and alphas toward heavier ions, strongly stimulated by a calculation by Clauser[3] on the energy deposition requirements with protons for small unclassified pellets of deuterium tritium. It was appreciated that the shorter range of heavier ions would permit the use of higher ion energy, greatly increasing the energy storable per ring and decreasing the ion current needed for pellet ignition. However, three problems seemed to present roadblocks in the path of the development of a total concept which could be realized with existing accelerator technology. These were (a) the intensity and brightness of existing heavy ion sources, (b) the fundamental limitation of storage time due to charge changing collisions of the lightly charged ions with each other, and (c) injection techniques which could ensure the ability to fill a storage ring to its space charge limit with singly charged heavy ions. These problems all appeared to be overcome conceptually with the suggestion of the feasibility of molecular dissociation injection[4] of I^+ from accelerated $(HI)^+$ molecules. As a result, a concept called "Hearthfire" was originated[5] and presented to a group of accelerator and pellet physicists in February 1976. A second distinctive feature of the "Hearthfire" concept was the use of 100 circulating bunches, simultaneously extracted by foil stripping and transported to the target in as many beams.

In the spring of 1976, a working group was formed at Argonne to investigate the practical feasibility of the proposed ideas. A detailed concept of an accelerator based system with components and techniques which appeared realizable within today's technology was developed. This concept, the fundamental uncertainties, and a number of alternatives were presented[6] to a group of accelerator and pellet physicists in a summer study in July sponsored by the U. S. Energy Research and Development Administration.

One of the conclusions of the summer study[7] was that heavy ion sources of 100 mA of singly charged ions with normalized emittance (area/π) of 0.02 mrad-cm are realizable with only modest extrapolation of existing source technology. If this projection proves correct, then the complex (and likely expensive) technique of molecular dissociation injection will not be required. In this case, the number of possibilities of different ions, charge states, and accelerator configurations capable of meeting the pellet requirements laid down[7] by the target working group of the study is very large. Since July, the activities of the authors have been concentrated on sifting out these many possibilities to discover the advantages and disadvantages of various alternatives before focusing on a second specific concept of an accelerator system for pellet fusion. This paper is a report of these studies.

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Beam Transport

It is well known that space charge forces can be dominant in the transport of intense ion beams. Such considerations impact strongly on the low energy end of a conventional accelerator; they will play a decisive role in the transport of intense ion beams from the accelerator or storage ring to the target for the pellet fusion application; and space charge considerations are particularly severe at the beginning of the linear induction accelerator. The importance of space charge forces to ion beam fusion is demonstrated by the presence of two papers on the subject[8] at this conference.

Conventional accelerators for heavy ions in which the ion energy is less than 2 MeV from the dc preaccelerator will require a special design of the initial stages of RF acceleration in order to accommodate a projected current of 100 mA with such low velocities. At the moment, the spiral structure appears to be superior to either the Wideroe or split ring because the shorter cavities allow more closely spaced quadrupoles. The current carrying capability in the presence of strong space charge forces is, therefore, greater. However, the feasibility of acceleration of high currents of 750 keV heavy ions in any RF structure is far from assured. For such low velocity ions, the structure must operate at a low frequency. A spiral resonator operating at 12.5 MHz would have a three turn spiral, and the mechanical stability of this structure (with beam) remains to be demonstrated. Existing spiral resonators operate at higher frequency.[9] The Wideroe structure has many drift tubes per cavity and is thus classed as a constant beta profile structure. It does not seem suitable for the present application (at least in the initial stages) because the structure lacks the flexibility to accommodate the wide range of ions and charge states still necessarily considered. For both the split ring and the spiral structures, the cavities can be separately phased to accelerate a considerably wider range of q/A and initial velocities. The lesser flexibility of the Wideroe may be an important disadvantage.

One of the lessons learned from investigations of the limitations of low beta RF accelerators is the strong desirability of achieving as high a voltage and initial velocity as possible in the preaccelerator. Multi-megavolt power supplies for dc accelerators appear capable of the requirements for beam currents in the 100 mA range. However, the ability to accelerate heavy ion currents of 100 mA on a pulsed basis has never been demonstrated and dc ion currents are normally at least two orders of magnitude less. In addition to problems of electron and negative ion backstreaming and numerous modes of electrical breakdown with potentially serious results at several million volts dc, questions of space charge in transport of the beam through the accelerating column will dominate and limit the maximum current at which the accelerator will operate. Higher gradients in the accelerating column than are normal in multi-megavolt heavy ion dc accelerators are clearly called for, and some form of focusing along the column would be most advantageous. The latter has been tried without success in some configurations although there are many others. The possibility of significant improvement in ion current capability looks promising with a well thought out R & D program. A particularly important step will be to provide good accessibility to ion sources and accelerating columns that are contained in pressurized vessels. In this respect, it seems to be advisable to take the accelerating tube out from within the rectifier stack.

Parametric Studies

As stated above, if adequate source current and brightness of a number of ion species can be produced, the range of possible accelerator configurations to satisfy the requirements of ion beam fusion is very large. As a first step to define and possibly narrow the choices, one must examine the technical constraints. There may be, in fact, no rigorous technical constraints, only judgments on present technical credibility. The latter could change with time or with purposeful R & D. Nevertheless, we proceed to set down such a list to begin the exercise. Only the simplest accelerator configuration, that of a full energy linear accelerator and one or more accumulator rings, is considered here.

Assumed Constraints

1 mm $\le$ r $\le$ 1 cm (r = target size)

P (60% of energy) = 600 TW

Q = 10 MJ

Q/M = 30 MJ/g

ϵ = emittance $\le$ 16 mrad-cm

I_C = circulating current $\le$ 20 A

Filling time $\le$ 100 ms

S = number of turns injected $\le$ 20 x 20

L = longitudinal compression $\le$ 100

N_B = number of beams transported $\le$ 100

$$K = \frac{I_{target}}{I_{source}} = S \times L \times N_B \le 4 \times 10^6$$

The above target requirements are those given by the target group at the summer study.[7] There needs to be some limit placed on the allowable emittance of the circulating beam in any accumulator ring, both because of the difficulty of construction of a magnet with too large an aperture and the difficulties of extracting a beam of large size. There is some feeling that the restriction on emittance should be even more severe. Restricting the average circulating current in a ring to 20 A seems conservative in view of the 40 A of protons achieved in the ISR rings. However, this value is also the maximum that can be achieved with a 50 mA linac current and the proposed maximum of 400 turns of injection. Moreover, heavy ion beams of this current have not been observed and one might be concerned about unknown instabilities at much higher currents. The limit to 400 turns injection into a ring implies 20 turns each into horizontal and vertical phase space. To accomplish this efficiently will require development of injection techniques, although conceptually the solution is straightforward. The longitudinal compression of 100 includes the effect of normal bunching such as required for acceleration. Such bunching can easily be a factor of 10 (B_f = 0.1) so that longitudinal compression by only an additional factor of 10 is required. The limit of the number of beams transported is arbitrary, but one should not utilize more than some fraction of the surface area of the reactor vessel for beam apertures, say 10%. This number of beams should be greater or equal to the number of rings required to accumulate the 10 MJ of stored beam energy.

It appears possible to adjust accelerator parameters such that the factors S, L, and N_B can be interchanged so as not to exceed the assumed limit of any one provided their product does not exceed 4 x 10^6. It is, therefore, instructive to examine the range of choices allowed by the current multiplication factor K. Figure 1 shows a plot of K vs. the linac voltage V (ion energy E = qV, where q is the charge state) for the 600 TW target requirement. (The beam energy must be 10 MJ; and if all of the beam were delivered in the peak pulse time of 10 ns, i.e. no pulse shaping, the peak beam power would be 1000 TW. The latter power has been used in computing the relationship between V and K and is plotted in Fig. 1.)

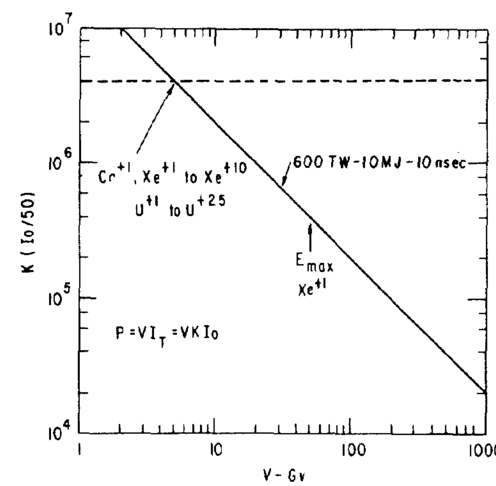

Fig. 1 Current multiplication factor vs. linac voltage for high confidence target case. Source current I_o is in mA.

The curve of Fig. 1 exceeds the maximum value of K (assuming the linac current is 50 mA) at a voltage of 5 GV. This value then is the minimum linac voltage. The maximum energy of xenon (for this target case) within the target requirements stated above is about 50 GeV. Accelerator systems (in this case, linac plus accumulator rings) can be designed to meet all of the target requirements with Xe^{+1} ions at any energy between 5 GeV and 50 GeV. For this particular type of accelerator configuration, minimum cost is very apt to be for the 5 GV linac voltage because of the high cost of linacs even though it implies many accumulator rings. For Xe^{+2}, one sees that one can satisfy the requirements with any linac voltage between 5 GV and 25 GV, corresponding to ion energies of 10 GeV to 50 GeV. For Xe^{+10}, the only suitable linac voltage is 5 GV, giving the maximum ion energy of 50 GeV. The range of xenon charge states for which an accelerator system can be designed to meet these target requirements without exceeding the limit of K = 4 x 10^6 is, therefore, from +1 to +10. The range is different for other ions. The range of charge states for various ions is shown in Fig. 1 in the upper left where the target requirement curve intersects the assumed maximum allowable value of K.

Choices between these many alternatives will depend strongly on relative costs of the accelerator systems among other factors. We have begun a program to systematically examine economic aspects of various options. Preliminary results indicate that for linac accumulator systems, the most economic system favors higher charge states. These results, presented at this conference,[10] are not conclusive, however; and the study is continuing to examine many other factors. One of these is the accelerator efficiency, which could become very important in determining the practicality of a particular accelerator system as the ignition source of a fusion power plant.

Ion Sources

In addition to the dependence of the relative cost of accelerator configurations on ion species, many other factors may be important in the final choice of ion species. Such factors relate to demonstrated source performance in terms of current, brightness, and reliability, cross section for ion-ion charge exchange, and engineering consideration such as ion reactivity with surfaces and condensibility of ions. The latter could be important for achieving a high pumping speed at the source to alleviate serious problems of high gas pressures in the accelerator columns.

The cross section for ion-ion charge changing collisions should be lower for singly charged ions of lighter mass. For these reasons and because of other advantages discussed below, $^{131}Xe^+$ and $^{133}Cs^+$ seem good choices for ions in the mass range of iodine; $^{209}Bi^+$ and $^{200}Hg^+$ are reasonable choices for ions in the mass range of ~ 200 nuclear masses. All seem quite promising from the point of view of source technology.

The 100 mA current required of a Cs^+ surface ionization source can be obtained by scaling up the 9 mA source of Kuskevics and Thompson[11] or by scaling down the 900 mA ion thruster of Ernstene et al.[12] A cesium surface ionization source is unique and ideal in that, unlike a plasma source, it produces only low temperature singly charged ions from a solid emitter of fixed shape and position. On the basis of these characteristics, it may be considered superior to any other known source of heavy ions. However, Cs^+ may have a potentially fatal flaw (shared by several other candidate ions) in that deposition of cesium on accelerating electrodes may lower the breakdown voltage to a prohibitively low value; whether it actually does or not awaits experimental determination.

Xenon is a good choice because it is a heavy noble gas. The unit cost of isotopically pure xenon is relatively high, but the amount of gas used is low enough that this is not a serious drawback. To obtain high percentage yields of Xe^+ (approaching 100%), discharge voltages of 20-40 V are used (typical of ion thrusters and CTR neutral beam sources of the Lawrence Berkeley Laboratory type). With these voltages, sputtering, which can present problems with discharge voltages of ~ 150 V, should not be excessive.

The ion $^{209}Bi^+$ might be a good choice[13] because it has a closed electron shell (hence, lower cross section for ion-ion charge changing collisions) and has an adequately high vapor pressure at 800°C. Considerable experience exists with mercury ions in the ion beam thruster field. Making use of existing applicable experience would seem to be very advantageous for the ion beam fusion program.

Hughes Research Laboratory, Malibu, California, has coupled a single aperture Pierce extraction electrode configuration with an ion thruster plasma source to give an ion source which can produce 5 mA of 100 keV argon ions. The brightness of this source is considerably in excess of that required for ion beam fusion.[14] Using this type of source with xenon or bismuth or mercury and scaling it in size and voltage to produce a 100 mA, 750 keV singly charged beam with a sufficiently small emittance appears to be feasible. This possibility is being explored with Hughes Research Laboratory.

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