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ACCELERATORS FOR FUSION: A PANEL DISCUSSION

(Summary Prepared by F. T. Cole)

An informal panel discussion on the use of accelerators for controlled thermonuclear fusion (CTR) was held at the Conference on Wednesday, March 16. The participants were:

Chairman: Fred Mills, Fermi National Accelerator Laboratory

Panel Members: Denis Keefe, Lawrence Berkeley Laboratory; Bogdan Maglich, Fusion Energy Corporation; Ronald Martin, Argonne National Laboratory; Alfred Maschke, Brookhaven National Laboratory; Marshall Rosenbluth, Institute for Advanced Study; Ravindra Sudan, Cornell University; Gerold Yonas, Sandia Laboratory.

Each panel member gave a presentation of his ideas. There was then discussion among the panel and, at the end, a period for questions from the audience.

Maglic discussed his MIGMA accelerators, a concept quite different from that of most CTR devices. The energy needed to initiate the reaction is supplied as the ordered motion of a beam, not as the thermal energy of a Maxwell distribution. Beam energies of several MeV are needed. At these energies, charge exchange between ions and multiple-scattering loss modes have decreased enough that fusion reactions can dominate. The MIGMA geometry is designed to provide an "automatic" return of ions to the central collision region so that their probability of undergoing fusion reactions becomes larger.

It is also possible to utilize "advanced" fuels in this concept. The reaction

$$He^3 + He^3 \rightarrow He^4 + p + p + 13\ MeV$$

appears at present to be marginally possible. It is not known at present how to produce the reaction

$$B^{11} + p \rightarrow 3\,He^4 + 8.6\ MeV$$

in CTR abundance. Both these reactions are "clean" in that their products are all charged particles, which are much easier to shield than neutrons. One may also hope to extract their energy electrically rather than thermally. At present, the MIGMA work is concerned with the "semi-clean" D-D reactions

$$D + D \rightarrow He^3 + n + 3.3\ MeV$$
$$\rightarrow H^3 + p + 4\ MeV.$$

Maglic described a series of three MIGMA accelerators, of which the latest, MIGMA III, operated in April, 1976, achieved a density of $3.5 \times 10^8\ cm^{-3}$ and a confinement time of 2.2 sec. MIGMA IV is in the design phase.

In closing his presentation, Maglic emphasized again that his fundamental point is to achieve high collision energy, not high temperature.

Yonas discussed the application of pulsed-power technology to CTR. This technology was developed by the Department of Defense for nuclear-weapons simulation work. There have been four general approaches to the use of pulsed-power technology in fusion:

(i) Relativistic electron beams
(ii) Light ions
(iii) Magnetically imploded plasmas
(iv) Heavy ions.

Yonas discussed relativistic electron beams and their use as a high-density driver to compress DT fuel to CTR densities and temperatures. By 1972, these electron beams were delivering more than 1 MJ at a rate of 10 TW. The DT fuel is in the form of a pellet and the objective is to heat the outside of the pellet shell to implode it to thermonuclear ignition. ERDA is sponsoring work on three kinds of ignition systems: glass lasers, gas lasers, and charged-particle beams. None of these systems has ignited fuel as yet; all are working toward a demonstration.

Yonas then described a series of electron-beam devices, HYDRA and PROTO I and II. The last of these has produced 8TW and has a 10 nsec pulse. A new device EBFA, to be complete in 1979, will produce 40 TW. A description was given of the pulse lines and diodes of the system.

In the work so far, all targets have been uniformly heated and there have been no gross instabilities in the target, which had been a worry. In response to a question concerning instabilities in the electron beam itself, Yonas answered that no filamentation of the beam has been seen, but there has been kinking in some situations with transient flow. When the beam is uniform, it is very stable.

In response to another question concerning designs beyond the 40 TW range, Yonas answered that he is thinking toward 100 TW designs. There is a fundamental problem of dielectric breakdown at these levels and magnetically insulated electromagnetic wave propagation is being studied. Recent work indicates that it is possible to achieve much higher power densities in this way. He commented that there are also problems of high-power beam transport over large distances if one is to ignite a high-gain pellet.

Rosenbluth began by saying that he would discuss a "humble" type of accelerator that has become the backbone of magnetically confined fusion systems. Plasma heating by injection of beams is being studied in these devices, because ohmic heating cannot produce the high temperatures needed for thermonuclear reactions. Charged-particle beams will only penetrate a distance of the order of a gyroradius and have instability problems to boot. Work is therefore being done to develop neutral-beam accelerators, which will give much greater penetration into the plasma. Ion beams are accelerated to approximately 150 keV, then neutralized in a charge-exchange neutralizing gas cell. A total of 10 neutral-beam injection points is planned for TFTR (Tokamak Fusion Test Reactor) now being built at Princeton. One might get 2 MW of neutrals out of this system, then inject them across the magnetic field into the plasma, where they will become ionized.

The experimental results that have been achieved to date are that the energy density in the beam is comparable to the thermal energy in the plasma and that the slowing-down rate of the beam is predicted by classical theory. Ion-temperature rise is about 900 eV, electron-temperature rise is about 300 eV. New experiments on PLT at Princeton are expected to produce temperatures of 5 keV by neutral-beam heating.

Rosenbluth separated fusion reactors into two generic types, those in which reactions occur by the interactions of the beam itself with the plasma (driven reactors) and those in which the neutral beam heats the plasma (ignited reactors). The first type requires the product of density n and confinement time τ to be at least 3×10^{13}, while the second requires $n\tau \gtrsim 3\times 10^{14}$. On the other hand, the Q's are marginal in driven reactors even for the D-T reaction.

In both cases, the principal limit is ionization of the beam by impact. The range a is proportional to the energy E and inversely proportional to n and Z_{eff}. For driven reactors, $na \gtrsim 10^{16}$ and $E \gtrsim 150$ keV. For ignited reactors, $na \gtrsim 4\times 10^{16}$ and $E \gtrsim 600$ keV. But neutralization is inefficient above approximately 100 keV for D^+. A proposed solution is to utilize a D^- source of 50 to 100 A. A second technique is to achieve efficient recovery of the energy of the charged fraction ($\gtrsim 150$ keV). A final idea might be to do so-called "ripple trapping," where ions are trapped in a ripple of the toroidal field after the low-energy neutral beam is ionized.

Sudan discussed the application of pulsed-power technology to the acceleration of ions. While it is easy to extract electrons from a surface, protons require a plasma. Reflex triodes and magnetically insulated diodes (a diode with a magnetic field normal to the flow to prevent electrons from crossing the gap) have been developed to produce a dense plasma anode in a short time (10^{-8} sec). Currents of 100 kA at 200 to 300 keV have been produced, with pulse lengths of 70 nsec and current densities of 50 A/cm^2. Some of these parameters are being improved in work at Sandia and the Naval Research Laboratory.

Thus one can produce accelerated protons with high efficiency. Their use as ignitors for pellets is being studied. In this connection, studies are being made of propagation of beams for distances of the order of 10 m in the possibly hostile plasma environment of a reactor chamber and of ion-beam to pellet coupling.

Experiments at Cornell have shown that high-current beams rapidly neutralize themselves with electrons pulled from the walls near the source. This space-charge neutralized beam in a plasma will also have current neutralization. The induced return current will cancel the self-fields in a time determined by the conductivity σ. There can be two-stream instabilities arising between the beam and plasma. There are also possibilities of actual reversal of the current and consequent defocusing of the beam. These are the kind of phenomena one may study in the beam-plasma system.

In the discussion, it was commented that these effects are particularly important for ions of large Z value. In addition, it has been observed in experiments that two-stream instabilities are saturated because the oscillating electric fields are so strong that they ionize the background gas. These instabilities might then increase the Z value and produce the current reversal.

Martin began the discussion of ion-beam fusion. The target requirements in such a system (given by the Livermore group) are that a high level of confidence in ignition would be given by a beam that deposited 600 TW power and 10 MJ total energy, 30 MJ/g, with the last 60% of the energy in a time of the order of 10 nsec. What is new about heavy-ion fusion is achieving this terrawatt power by gigavolts and kiloamps rather than megavolts and mega-amps. Existing technology gives stored energies of megajoules, at Fermilab, ISR, and SPS. There is considerable experience with accumulation, but little with time compression, from 10 μsec to 10 nsec. There are two kinds of schemes being considered, one with many short bunches around the accelerator making many short beams that are extracted and combined, and another with rapid strong longitudinal bunching beyond the space-charge limit. This second kind of scheme is discussed by Maschke later. A combination of these schemes looks straightforward and interesting.

The constraints on the beam appear to be

Beam radius:	$1\ \text{mm} < r < 1\ \text{cm}$
Emittance:	$\epsilon \le 16$ cm-mrad
Circulating current:	$I_c \le 20$ A
Accumulation time:	$T_c \le 100$ msec

Current multiplication $K = SLN_B$, where S is the number of injected turns, L is the longitudinal compression, and N_B is the number of beams. With $S \le 400$, $L \le 100$, $N_B \le 100$, we have $K \le 4\times 10^6$. Thus a 50 mA source could give 200 kA on target and 5 GeV × 200 kA = 1000 TW. We need an energy greater than 5 GeV to keep $P > 600$ TW and $K < 4\times 10^6$. One could achieve $P = 600$ TW and $K = 4\times 10^6$ with ions from U^{+1} or U^{+25} all the way down to Ca^{+1}. There is an upper limit on energy arising from the requirement that $r > 1$ mm. This gives 50 GeV for Xe^{+1}, for example. The parameter space is thus very large.

Keefe continued the discussion of heavy-ion fusion, concentrating on the choice of the accelerating system. The parameter regime of lightly charged very low velocity heavy ions and high power are quite different from most of our previous experience. The synchrotron, the rf linac, and the induction linac are the systems usually discussed as choices for supplying most of the kinetic energy.

The equivalent accelerating gradient in a circular accelerator is $T_f/2\pi R \sim 25q$ MeV/m, which is much higher than that in a linear accelerator ($\sim 2.5\,q$ MeV/m), but the circular accelerator has space charge to deal with. That is, in the linear accelerator, the tune change $\Delta\nu \lesssim \nu$, whereas in a circular accelerator, $\Delta\nu << \nu$. Space charge will tend to drive the circular design more toward the parameters achieved by linear accelerators. In addition, the circular accelerator has large pulsed stored energy, which is on the wrong side of the energy budget.

It is of interest also to consider the induction linac, which has large peak power, but very low average power. One can envisage a sequence of cavities, first iron, then ferrite, then radial lines. The system becomes cumbersome for currents less than 100 A, so that one needs a single-pass injector for something like 200 MV at 100 A. This system may be very long, because the length scales up with the charge state q, while the length of the induction linac is inversely proportional to q. This is quite different from the case of an rf linac feeding an accumulator ring.

Maschke discussed multiple accumulators with a linac feeding them. One can stack in horizontal phase space in one set of rings, then in vertical in another set so that in M clusters of N rings, one has MN accumulators. All the rings can be filled in a few milliseconds with a linac and therefore beam-beam interactions are a small problem even if the cross sections are large.

Maschke argued that the gain of a pellet system is finite and that therefore large average beam power is needed. The linac is the only device that can now produce hundreds of megawatts at not unreasonable capital cost. The linac-accumulator might cost 75 M$/GV and produce 10 MW of average power. With a pellet gain of 200, this would contribute approximately $0.11/W compared with overall plant cost of $0.75/W. Any system must produce beam power at $5 to $10 per watt to be competitive. At this time, the linac is the clear candidate.

Maschke suggested the need for relevant experiments to uncover the key technical factors that will lead to more economical designs. He reported on a recent experiment done by Gordon Danby, John Keane, Edward Gill, and himself at the AGS. These are preliminary results. The aperture was stopped down vertically to have an acceptance of the order of 0.5×10^{-5} m-mrad, with perhaps 20 times that horizontally. The rf system was banged on hard to 400 kV/turn. The beam bunched in approximately 8 turns and had an instantaneous current of 1.6 A. For that beam size, one can deduce that the vertical space-charge defocusing force corresponded to a tune shift $\Delta\nu = 1.9$, many times the conventional limit. There was no indication of harm to the beam. They had hope for a $\Delta\nu$ of 4.5 but the energy spread of the linac was too large to get a tight bunch. A debuncher now being built will help this.

Some other problems Maschke mentioned as important were the loss of beam in multiturn injection; half the beam is lost in AGS injection. Almost no loss can be afforded with megawatts of beam power in accumulator rings. Experiments are needed to demonstrate this clean injection. Experiments are also needed to find the limit of longitudinal bunching factors.

In their closing remarks, the panelists made the following points:

(i) Maglic suggested the need for a 3 MV, 50 mA accelerator and for a decelerator to extract energy. He emphasized his criticism of plasma heating as a method of achieving thermonuclear reactions.

(ii) Yonas suggested a marriage of the technologies of pulsed power and of linear induction accelerators, particularly in Marx generators and gas switching. He also pointed out the interest in collective acceleration for the difficult low-velocity stage.

(iii) Keefe responded that collective acceleration to 100 MV would be extremely interesting. There might be questions of beam quality and energy spread and these should be explored.

(iv) Rosenbluth asked whether these large accelerators didn't make ridiculous scenarios for a power station (a planted question). Keefe responded by showing an artist's description of a power station approximately 2 miles long in a familiar setting south of San Francisco. More seriously, he showed photographs of existing fossil-fuel power stations that are of the same order in size.

(v) Sudan asked whether high-current beams might not become neutralized as high-current beams in plasmas do, making it difficult to transport them. Maschke responded that one might be able to keep a beam from neutralizing by keeping it tightly bunched.

(vi) Martin expressed the opinion that pellets can indeed be ignited. It is not yet clear, he said, what is the best accelerator configuration, the best ion, and how much it will cost. It was agreed that the choices look very difficult at this early stage. Yonas pointed out that pellets have not yet been ignited and that there is much hydrodynamic study to be done.

(vii) Maschke commented that there is a wide range of target parameters and many more complicated configurations. He suggested that one might propel a small rocket ship (a pellet) to 30 MJ/g by ablation. One might also use a uranium beam to heat a plasma confined in a long solenoid.

(viii) A question in the audience asked why heavy ions are superior to photons. The answer given was that they deposit energy in a small range (because of the Bragg peak) and that they can be transported more easily.