Title
RAPPORTEUR TALK FOR IAEA FUSION MEETING, BRUSSELS

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Publication Date
1980-07-01

LBL-11429
HI-FAN-114

Rapporteur Talk for IAEA Fusion Meeting, Brussels
(P-4)

July 1980

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1. Introduction:

A promising candidate for a fusion power plant driver is an accelerator that can produce intense beams of heavy ions ($A > 200$) at energies of about 10 GeV. Adequate repetition rate is ensured by borrowing from existing accelerator technology and it can be shown that overall wall-plug efficiencies in the range 10-30 percent can be achieved.

The need to achieve suitable specific energy density (> 20 MJ/g) in a target capsule a few millimeters in radius determines that the ion kinetic energy must not be far from 10 GeV.

Target capsules with either single or double shells can be used. They can be driven ablatively or, alternatively, in a "cannon" fashion which becomes an option for ions because of the volumetric nature of the energy deposition. A target of the latter kind would have a thin layer of lead overlying a lower density material. The ions will penetrate the lead layer and deposit most of their energy in the second layer; the lead then acts as an inertial tamper and the expansion of the low-density plasma is directed inwards to implode the fuel.

From target design considerations the latest estimates for a fusion power plant design are:

Energy/pulse = 3 MJ
Ion Kinetic Energy = 10 GeV
Power = 150 TW
Repetition rate = 1 - 10 Hz

2. Accelerator Drivers

To meet the above conditions the accelerator design needs to be extended from present practice with research machines in two important regards. First, the power on target is very large implying a final beam current of 20 kA which can be achieved by subdividing the output accelerated beam into some ten or twenty beamlets before entering the reactor. Second, while it is known that intense beams can be produced at low energies that have optical quality (low emittance) good enough to allow the final target optics to be achieved, the various beam manipulations inherent in any accelerator system can only dilute this quality; the extent of this dilution must be very carefully controlled within narrow limits.

Two distinct driver systems show good promise of meeting these goals. One uses an rf ion-linac to accelerate about 1/10 ampere of beam current to full energy in a train of short pulses that lasts for ~ 1 msec. Thereafter the low-current beam is injected into an array of storage rings which accomplish the current amplification, first by the use of multi-turn injection and, second, by tight bunching of the beam with an r-f system.

The other system relies on the induction linac which has an accelerator structure inherently suitable for high currents. Relativistic electrons have been accelerated in this way at beam currents 1 - 100 kA. For non-relativistic heavy ions the beam can be bunched and the current amplified continuously along the machine by creating some incremental acceleration of the tail of a single large bunch with respect to the head. From 10 amps at injection the current is increased to a few thousand amps at the end. Thereafter the beam is split transversely into beamlets that are then brought to the target.

3. The Argonne Heavy Ion Fusion Program: Accelerator Demonstration Facility (Phase Zero)

Examination of a reference design for an rf/storage-ring system developed at Argonne National Laboratory shows that there are two parts of the system where the beam-current is high enough to be substantially beyond the range of present experience with research accelerators, one at the low velocity end where handling the slow ions with very small charge-to-mass ratio is cumbersome and the other at full-energy in the storage rings. A study of the intense beam behavior at high current in the storage ring (including the effects of beam loss through charge-exchange) would have to await the building of a facility of significant size (e.g., the so-called 100 kJ HIDE).

Within the present modest budget for heavy ion fusion, efforts at ANL are directed:

- first, at demonstrating control of the beam manipulations needed at the low velocity end of the driver and
- second, at a later expansion of the system by addition of a longer linac, stacking ring, and synchrotron to produce a 3 kJ beam facility for experiments with solid density plasmas heated by ions to 50 eV.

The reference design shows that to handle the current early on a set of some 8 parallel low-frequency linacs are used initially. The output beams from a pair of these machines are combined transversely and injected into a succeeding linac of twice the frequency so that all its rf buckets can be filled. This binary process is repeated each time with a doubling of frequency until one has arrived at a higher current in a single linac.

The prefatory step of producing a beam of Xe^{+1} with adequately high current and low emittance at 1 MeV has been completed at ANL. Similar results at half this voltage were also achieved at BNL and LBL. After acceleration through a few independently-phased cavities the beam will enter a 12.5 MHz Wideroe linac (now under construction) for acceleration to 9 MeV. The next step in simulating conditions at the front end of a driver will be to deflect and inject into a second Wideroe working at 25 MHz. The Unilac uses frequency-doubling from one linac to a second but beam matching is done only in transverse phase-space. A crucial new part of the ANL test will be to arrange, in addition, for longitudinal phase-space matching to avoid dilution of the 6-D emittance. Thus the test will give quantitative answers on the overall emittance dilution to be expected from these manipulations.

Extension of this facility at later time would be by stripping to Xe^{+8} and accelerating to 220 MeV. Next would come demonstration of the ability to stack multiple turns in a ring by a novel method of injecting simultaneously into both transverse phase planes to keep the optical brightness high. The ring - which needs a large aperture 20 x 30 cm^2 and very high vacuum - could be pulsed to bring the beam from 220 MeV to 10 GeV and, by delivering 16 beams to a sub-millimeter target, could supply a 3 kJ beam development facility.

4. Multimegajoule Heavy-Ion Induction Linacs

The conceptual design of an induction linac *for electrons* is simple. Since the electrons are relativistic the bunch length, pulse duration and beam current remain constant along the whole machine. Thus the design process reduces to choosing a suitable induction accelerating module containing a torus of ferrite, of thin iron tape, or other ferromagnetic material, and building many identical modules of this kind. Between the modules are interspersed magnetic lenses which, for electrons, can be relatively weak.

For ions the situation is quite different. Moving at non-relativistic speed, a long bunch of ions can be bunched in space and time by differentially accelerating particles near the rear of the bunch with respect to those near the front. In this way the beam current can be made to grow along the machine as the acceleration proceeds. At all points, however, the current must be kept below the Maschke space-charge limit:

$$I_M = \text{Const.}\ (\eta B \epsilon_N)^{2/3} \ \left(\frac{q}{A}\right)^{1/2} \ V^{5/6} \qquad (1)$$

Where η = fraction of length occupied by lenses,

B = magnetic quadrupole pole-tip field,

q/A = charge/mass ratio of ion,

V = beam voltage = (Ion Kinetic energy/q).

The design can proceed by concentrating on a particular point in the machine where the beam voltage is V, and examining the options for adding another increment of voltage, ΔV. Call the beam current I, and the pulse duration, t, - note that the beam charge, (It) = Constant. If the magnetic transport channel is made weak i.e., widely spaced magnets and modest fields, I must be kept at a low value and t becomes large necessitating a large number of volt-seconds (ΔV t) of core to accelerate. Alternatively, at the other end of the scale, one could choose closely-packed high-field magnets in which case I could be larger, t shorter and the volt-seconds decreased. In the first case the magnets are inexpensive but the accelerating module cost high and the balance can be reversed in the second instance.

In order to constrain this design problem the criterion of "minimum cost" to achieve the voltage increment, ΔV, was imposed at each point along the machine. To do this a number of engineering designs were developed for the modules and the magnets, and a computer search for a minimum-cost arrangement carried out at each point within the constraint of Eq. 1 and some other practical constraints. In particular, the search for a minimum included cycling through various choices of ferromagnetic material; for example ferrite becomes preferred to iron for the shorter pulse lengths near the end of the machine where the design looks rather similar to an electron linac.

A major result is that to achieve Q megajoules the choice of final voltage, V_f, and corresponding charge (note $It.V_f \approx Q$) can be very broad without influencing the cost much. Also, the choice of ion is not critical. The efficiency of the cost-minimum examples lay in the range 12 - 25 percent depending on repetition rate. Note, however, the efficiency can be improved by departing a little from the minimum-cost criterion.

5. Fusion Applications of the Meqalac

The current limit for a single beam in a quadrupole transport system is a severe one, particularly at lower beam voltages. It was pointed out by Maschke that one can achieve currents greater than that given in Eq. 1, by accelerating a multiplicity of small beams through a given structure. As an illustration, consider n beamlets each with emittance ε_N / n ; then application of Eq. 1 shows that the summed current of all the beamlets (still with a total emittance of ε_N) is

$$I = n^{2/3} I_M$$

At velocities below about 0.1 c electrostatic quadrupoles can supply stronger focussing fields than magnetic quadrupoles. This advantage is further enhanced if one considers quadrupoles of small dimensions; the electric-field break-down limit goes up whereas the pole-tip field in electromagnets goes down. The MEQALAC (for Multiple-beam Electrostatic Quadrupole-focussed Linear Accelerator) can accelerate large currents by means of a matrix of electrostatic quadrupoles and is particularly useful for low-speed ions.

It should be noted that Eq. 1, or its analogue for electrostatic quadrupoles, represents an upper single-beam limit that must be obeyed but there are other limiting conditions that can enter at lower values than I_M. For example, from the requirements that a quadrupole be several times longer than its bore diameter if it is to act as a good lens, and that the transport be stable both for single-particle and space-charge dominated motion, one has:

$$I_Q(\text{amps}) < 1.7 \times 10^{-8} \left(\frac{q}{A}\right)^{1/2} V^{3/2} \qquad (3)$$

a condition that is independent of the emittance and restoring-field strength. For heavy ions V needs to be very high before one can escape this limit in a single beam; with multiple beams, however, large currents can be transported at modest beam voltages. Also, the I_Q limit for one large single beam results in ion sources operating well below their capability - going to multiple beams allows source emission to be increased to the Child-Langmuir limit on current density.

A model (M1) with 9 beams each with 4 mm radius has accelerated Xe^{+1} at low speed from 16 keV to 72 keV with close to the predicted performance in an rf linac with a frequency of 4 MHz.

At present nearing completion is a 750 kV proton linac operating at 200 MHz which carries an array of four parallel quadrupoles in each drift tube. It can provide a compact replacement for a Cockcroft-Walton injector. An exciting potential application for magnetic fusion would be to accelerate many tens of amps of H^- for neutral beam production and avoid the single high dc voltage problems. Also, the structure would be virtually opaque to back-streaming neutrons and tritium.

A variant using electrons (MEQATRON) is also under study for high-power rf generation. The multiple-beam array can use many individual sub-millimeter beamlets and thus could provide a power source at 100 GHz for ECRH. Note that the virtue of using high total currents is to enable one to achieve high-power without pushing the high voltage limits.

This work supported by the U.S. Department of Energy under Contract W-7405-ENG-48.