A DECADE OF ACCELERATOR R & D FOR HEAVY ION FUSION

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Motivated by early recognition of the unusual accelerator requirements for heavy ion inertial fusion, as well as the long term potential for energy production, a wide-ranging series of theoretical and experimental accomplishments have taken place during the past decade. Some results are of benefit mainly to heavy ion fusion, while others have broad applicability. In this review emphasis is given to high-current beams, induction linacs, use of multiple beams, longitudinal pulse-length compression and stability, electrostatic quadrupole focusing, radio-frequency quadrupoles, beam funneling and merging, ion sources, and conceptual designs for intermediate facilities as well as for full-scale fusion energy drivers.

Introduction

The prospect of thermonuclear fusion energy from magnetically confined plasma has spurred teams of researchers on an international scale since the 1950's. Inertial confinement fusion (ICF) began much later, on a serious scale in the early 70's. As the name implies, ICF depends on the burning of a small mass of fuel during the short time that it stays together by its own inertia. A 'driver', generating intense beams of particles or short-wavelength light, is used to compress and heat the nuclear fuel to the required conditions of density and temperature.

Fortunately, the pulse energy and peak power demanded from the driver to compress the fuel are far less than that required to heat the fuel directly to burn conditions. This fact is used to minimize the driver requirements. However, the energy and power density are still far greater than that achieved by any prior intense beam technology. Typical numbers are 4 MJ pulse energy and 500 TW/cm^2 power density (divided among 20-30 beams), in a pulse of order 20 nsec duration [1]. These challenging parameters made it obvious from the beginning of major ICF programs that complementary research on drivers as well as targets is vital to long-term success.

Laser drivers have an inherent advantage of high power density, which made them immediately suitable for target physics experiments using small targets. An impressive variety of basic research has been performed by the roughly dozen major laser-based international ICF research groups. However, a number of major issues confront the development of high-power lasers which have the other requirements of efficiency (>10-15%), repetition rate (2-10 Hz), and reliability, at acceptable cost [2].

Particle-beam ICF programs began with electrons in the early 70's, in part due to the availability of relatively inexpensive pulse-power technology for single-pulse experiments. In 1979 Sandia National Laboratories, the leading proponent of pulse power drivers, began a light ion program based on protons. More recently they have chosen lithium ions. In any case the peak current, tens of megamperes, makes the beam focusing problem enormously difficult.

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Heavy ion fusion (HIF) based on conventional multi-stage accelerators was proposed in 1974-75 by A.W. Maschke and by R.L. Martin and R. Arnold. Early references are summarized in a comprehensive 1982 review of ICF by D. Keefe [3]. The Department of Energy (then ERDA) organized a two-week summer study in 1976 to examine the method [4], and a small DOE-funded research program began in 1977.

A principal advantage of HIF is the reduction in beam current to the order of 30 kA total (typically 1 kA/beam), which can be handled with nearly conventional means. But HIF demands multistage accelerators to obtain GeV energy, which appear to be large and expensive. Whether this image corresponds to objective analysis is the subject of study and debate, and additional research. The only published comparative analysis indicates that HIF drivers compete quite well with lasers and light ions [5].

The accelerator R&D for HIF that began in 1977 has included a variety of topics. The purpose of this review is to summarize what I believe to be the most important accomplishments of the past decade for HIF, and for the accelerator community at large. The status of the several major HIF programs on an international scale is well summarized in the proceedings of the 1986 symposium [6]. No attempt is made here to review program status, nor to describe such important projects as the HIF Systems Assessment recently completed as part of the U.S. program. This project as well as others are included in the proceedings.

Space-Charge Dominated Beams

It was recognized at the outset that the most serious issue for the accelerator designer was the beam current, especially after it was concluded that the ion kinetic energy should be reduced to about 10 GeV or less for more optimum target performance. Use of multiple beams was a foregone conclusion, as was operation at the maximum possible current per beam. However, this latter parameter, despite decades of accelerator development, was not well understood. A.W. Maschke provided a formula for the 1976 summer study which seemed unfamiliar [7]. This formula and the HIF requirements themselves sparked a series of studies by a number of groups which have only been reasonably resolved during the last few years.

Theory, large-scale computer simulation, and experiments have all contributed to the present state of space-charge dominated beam physics. E. Courant confirmed the Maschke formula for the 1976 summer study [8]. In 1977 I. Haber of the Naval Research Laboratory began converting codes developed for plasma physics to the beam problem. These were adopted by the Lawrence Berkeley Laboratory (LBL) group and a fruitful collaboration developed [9].

In 1979 the Brookhaven group, led by Maschke, began scaled experiments with low-energy ions using electrostatic quadrupoles. Their design and setup, together with very encouraging results, were reported in 1983 [10]. Although DOE funds were not available to continue the BNL work, Maschke's "MEQALAC" design has been adopted and carried impressively forward by a group at the FOM Institute in Amsterdam, in collaboration with the University of Frankfurt [11].

The LBL group, led by D. Keefe, decided early on to mount an experimental and theoretical campaign to understand the beam current question. L. Smith, L.J. Laslett and coworkers developed analytic theory. The LBL team constructed an innovative system of 87 electrostatic quadrupole lenses arranged in a long FODO lattice. Known as the Single Beam Transport Experiment (SBTE), it included a suitable low-emittance source [12]. Meanwhile M. Reiser began a program at the Univ. of Maryland in both analytic theory and a series of low-energy e-beam simulation experiments [13]. In West Germany I. Hofmann and co-workers began similar programs. Later their codes were compared with experiments at Gesellschaft f. Schwerionenforshung (GSI) [14]. Also a group at the Los Alamos National Laboratory (LANL) desired better understanding of space charge in RF linacs at low energy, for several applications, including HIF [15].

The result of these efforts is a major advance. The LBL experiments on the SBTE are especially noteworthy. The LBL group mapped out beam transmission and emittance growth over a wide range of lens strength for low-emittance beams [16]. A few of the basic ideas are summarized here.

The definition of a space-charge dominated beam is best described using the generalized perveance K, which is the normalized beam current scaled to charge state, mass, and kinetic energy. It is defined as:

$$K = 2(I/I_0)(m/M)Q^2/(\beta\gamma)^3 \qquad (1)$$

following Lawson [17]. Here $I_0 = 10^7$ mc/e (MKS) = 17 kiloamps, I is the particle current, m is electron mass, M the beam particle mass, Q the charge state, $\beta = v/c$, and $\gamma = (1-\beta^2)^{-1/2}$. A space-charge dominated beam can then be defined as a beam which has sufficiently small emittance that $K > (\epsilon/a)^2$, where a is the beam edge radius and ϵ is the unnormalized transverse emittance, defined as in Ref. [17].

The LBL results can be summarized in terms of the phase advance per lattice, σ, in an alternating gradient (AG) system. σ is related to the usual betatron wavelength λ by $\sigma = 2\pi L/\lambda$, where L is the lattice period. The same formula defines the phase advance at low current, σ_0, in terms of the single-particle wavelength at low current, λ_0. The central question can then be phrased: to what extent can the ratio σ/σ_0 be reduced (or λ/λ_0 be increased) by the presence of space charge before the beam becomes unstable?

Maschke included in his 1976 formula a constant multiplier which he estimated primarily from empirical data. His estimate corresponds to $\sigma/\sigma_0 = 0.7$. Subsequent theory using the Kapchinskij-Vladimirskij distribution indicated that major instability would set in at $\sigma/\sigma_0 < 0.4$ and $\sigma_0 > 60^0$, but the realism of the distribution functions was questioned because simulation showed that more realistic beams might indeed be stable. Happily, the SBTE results have demonstrated stable transport for values as low as 0.1, provided that $\sigma_0 <$ 85-90 degrees. The LBL source emittance becomes the limiting factor at this point, so it is not yet known how much further down σ/σ_0 can be pushed, if at all.

Nonlinear effects may dominate the lower limit. For $\sigma_0 > 90^0$, the beam becomes rapidly unstable at high current, in general agreement with theory.

Progress in solving the basic envelope equation came in parallel with the experiments and with simulation. With the assumption of a uniform density beam and a "smooth approximation" for the external focusing force, a simple approximate solution has been obtained for the space-charge dominated limit, as follows:

$$a = (L/\sigma_0)(K)^{1/2} \qquad (2)$$

and $$K = (\sigma_0/\sigma)(\epsilon/L)\sigma_0 \qquad (3)$$

Thus, for fixed external focusing (L and σ_0), the perveance, hence current, is limited only by the depressed phase advance and is proportional to the transverse emittance, provided of course that the emittance is small enough to qualify the beam as space-charge dominated. The beam radius is independent of emittance and varies as the square-root of K.

Additional progress, motivated in part by HIF, has led to better understanding of the equilibrium dynamics of these beams. It turns out that uniform density, assumed for the simple solutions just given, is a minimum-electrostatic-energy distribution. Nonuniform beams rapidly (in < a quarter plasma period) become more uniform, and in the process convert their "excess" electrostatic field energy into transverse kinetic energy, resulting in emittance growth. The theory provides specific predictions for emittance growth as a function of the degree of nonuniformity.

Summaries of all of the above work may be found in papers by Reiser [18] and by Wangler et al [19], which also include application to the bunched beams of RF linacs. Important extensions to nonlinear effects have been studied by Celata et al [20]. Anderson has analyzed the mechanism of converting field energy into emittance growth [21]. Lee et al give a set of formulas which include experimental parameters such as the aperture fill factor and the maximum practical voltage on quadrupoles [22].

As a result of the pioneering efforts described above, accelerator designers can have a great deal more confidence in transporting and accelerating the high current associated with space-charge dominated beams. Although more work is needed, it would appear that beam currents up to three times those estimated a decade ago should be possible for a wide variety of accelerator applications.

Longitudinal Effects

Questions about longitudinal stability were also raised early in the HIF program. For the major designs under consideration during the decade, longitudinal stability issues are generally divided into two types: those associated with RF-linac based systems, primarily the longitudinal microwave instability, and those associated with the induction linac method, primarily the resistive wall instability. Significant advances have been made in each area, and are summarized below.

Before launching into stability studies, Lloyd Smith examined space charge effects in rf bunching, drift bunching, and induction linac bunching at the 1976 summer study [23]. At the 1977 workshop Judd studied bunch compression in the beam lines between the accelerator exit and the target [24]. Neuffer extended their work, using a self-consistent distribution in longitudinal phase space, and examined the resistive wall instability [25].

In 1981 Bisognano et al began studying nonlinear and dispersive effects in the propagation and growth of longitudinal waves, using particle simulation based on a 1-D model [26]. Both Bisognano et al and Neuffer found potentially damaging wave growth.

Then in 1983 Bisognano, Haber and Smith published a more detailed analysis with very encouraging results for the longitudinal stability of induction linac bunches [27]. I quote from their summary:

"The induction linac bunches of heavy ion fusion scenarios are strongly influenced by the longitudinal space charge impedance. This is in direct contrast to relativistic bunches in storage rings where most of the data on stability have been obtained. Simulation results reveal that when space charge effects are large, the stability requirement of small growth rate relative to the synchrotron frequency for relativistic bunches is replaced by the relaxed condition of small growth rate relative to the frequency spacing of the space charge wave modes on the bunch. Dispersive effects from finite pipe size tend to make the lower frequencies less susceptible to instability than higher frequencies. Since induction modules have a high resistive component only for the lowest bunch modes, stability is better than would occur for a broadband impedance of comparable magnitude. These results indicate that long term longitudinal bunch stability is realizable for induction linac drivers for heavy ion fusion".

Consider next the microwave instability. While well understood for relativistic beams, application to high-current non-relativistic beams was not clear. The problem is most severe in the final accumulator rings of RF-linac based systems, where the maximum possible currents must be held for times up to 5-10 msec before being ejected and brought to the target. While this is far less than the hours, or even days, of high energy physics storage rings, it is still a crucial parameter for HIF designs. Progress in this area is most easily described by referring to the studies performed in connection with the West German-Univ. of Wisconsin HIF system design called HIBALL. A similar design effort was performed by a collaboration of several groups in Japan, called HIBLIC [28].

HIBALL is a point design for a large power plant system based on an RF linac/storage ring driver. Extensive design studies were done by a large group, including fundamental studies of the stability limits of storage rings for non-relativistic beams. Initial calculations were submitted to the 1982 HIF Symposium participants, critiqued by key experts and, after some redesign work, published as HIBALL-II [29].

We confine our attention here to a summary of the stability studies for HIBALL-II. The most interesting results were first reported in 1983 by Hofmann et al [30]. With analytic theory and computer simulations they showed that the onset of the longitudinal microwave instability should be suppressed by Landau damping, due to the formation of a stabilizing tail in the momentum distribution function. The tail involves at most a few percent of the beam. They also analyzed the stabilizing effect of finite bunch length. Their calculations indicated that 30-fold bunch compression should be possible without loss, using two RF harmonics. Hofmann reported additional encouraging calculations in 1984 which indicated a safe storage time of 5-10 msec [31]. In this connection continuing experiments on the Rutherford ISIS synchrotron should prove to be extremely useful in comparing with the theory [32].

Multiple Beams and Injectors

In this section we briefly summarize a number of accelerator developments and designs which have occurred as a result of HIF programs, with emphasis on innovation and in some cases broad applicability.

The first innovation that comes to mind is multiple beams. With a very definite limit imposed on the current in a single beam, multiple beams are a must. Most HIF designs fall in the range 10 to 40 beams, except at the source, where more may be required. Seminal in this development were the ideas of Maschke, to incorporate AG focusing for multiple beams into a resonant RF linac tank structure [10, 11]. For induction linacs, the LBL group developed designs which maintain separate AG focusing for each beam, but thread all of the beams through common induction gaps [33]. This technique has an obvious cost advantage compared to separate structures. A novel injector system, using 16 beams in a common high-voltage tank, has been under development at LANL for later use in the LBL program [34].

Experimentally, the LBL group has developed an impressive scale-model accelerator called MBE-4, for Multiple Beam Experiment with 4 beams. It is designed to provide acceleration and pulse compression by means of voltage ramping, at the space-charge limit, as well as a test of multiple beams. Preliminary results with about one-half of the accelerator have been successful [35]. Also, no significant beam interaction problems have been encountered.

HIF programs have also contributed to radio-frequency quadrupole (RFQ) development. Invented in the USSR, developed at LANL, RFQ's have spread rapidly [36]. Their strong focusing power is particularly effective for counteracting the space charge of low-velocity heavy ions. The GSI group, motivated by their HIF program as well as nuclear physics and other applications, decided some years ago to build a new RFQ injector for UNILAC. At the 1986 Symposium Muller reported on the status of the new injector, called MAXILAC. For ions up to mass 127, MAXILAC is designed to increase the beam current of UNILAC dramatically [37]. A novel split coaxial cavity is employed, operating at 13.5 MHz.

I.M. Kapchinskij et al report on a heavy ion RFQ operating at 6 MHz which is a prototype for a HIF driver injector. It is designed to accelerate up to 32 mA of Bi^{2+} [38]. N. Ueda et al report on tests of an RFQ linac "TALL" which uses a more common frequency, 100 MHz, to serve as part of the injector system for a synchrotron facility at the Institute for Nuclear Studies [39]. The Frankfurt group has also developed an especially interesting geometry based on the use of four rods instead of vanes [40]. In addition to simpler manufacturing, this geometry allows the possibility of multi-beam RFQ structures based on an array of rods (see Fig. 6 of Ref. 40).

While most RF-based HIF designs use either 16 or 32 beams at the source, the main RF linac employs a single beam. The term 'funneling' refers to the process of combining alternate RF bunches of adjacent beams into a single beam having twice the frequency. Phased RF fields are used for transverse deflection. Funneling must be done in several stages to combine 16 or 32 beams into one, each stage being done at a higher energy where the relative space charge forces are smaller. Both HIBLIC [28] and HIBALL-II [29] employ such an arrangement, called a linac 'tree'. In principle, funneling can increase the beam brightness (current divided by the product of x-and y-emittance) by a factor of two at each funneling stage.

The linac tree concept is straightforward, but an important issue is the emittance growth during funneling. Bongardt and Sanitz have studied the process in some detail and find "tolerable" emittance growth, but recommend further studies to better understand it, especially regarding the effect of non-linear space charge forces [41]. Stokes and Minerbo propose an innovative method which provides the transverse deflection directly within an RFQ, thus retaining the strong focusing force during the funneling process [42].

A similar question exists for the induction linac method. Current LBL designs call for 16 beams in the main linac, but at the source 64 beams may be required to provide the total current. Merging by 4 to 1 is then necessary at an energy of perhaps 100-200 MeV for minimum total cost. Again the issue arises of emittance growth due to space charge effects. C. Celata has begun studies of the problem and finds growth of about a factor of two for "experimentally reasonable " parameters [43]. This would appear to be within a normal allowed 'budget' of emittance growth, but experiments are necessary.

Ion sources represent another important area of definite progress. A number of sources are now available from which HIF system designers can choose. For induction linacs two recent additions stand out. Brown has developed a metal-vapor vacuum-arc source which is rich in higher charge states, e.g. 2,3,4,and 5 in some cases [44]. This coincides nicely with the recent conclusion of the U.S. HIF Systems Assessment project, that use of charge state 3 leads to dramatic reduction of the driver cost [45]. Another source, developed at the University of New Mexico, features grid control of the plasma from a metal-vapor vacuum arc [46]. It is currently a leading candidate for use in the 16-beam LANL injector system [34].

Early in the LBL HIF program, when electrostatic drift tube linacs were studied for the injector system, a unique contact ionization source was constructed which yielded 1 ampere of Cs ions [47], but is not appropriate for current accelerator designs. Among recent reviews of ion sources, I point out those of R. Keller [48, 49]. Discussions of the GSI sources are contained in these reviews, as well as in the HIBALL-II report [29]. Also, Spadtke and Keller studied in detail, with simulation and experiment, the formation of high-brightness beams, considering both the source and preaccelerator [50].

Plans and Summary

Both the GSI program and the Japanese program are heavily intertwined with their respective nuclear physics and other programs related to their major facilities. Both are planning high-energy heavy ion synchrotrons which are not directly applicable to HIF. However, their indirect benefit is substantial. At GSI, for example, an additional storage ring with cooling capability has been funded as part of the overall facility which will allow a number of experiments of direct benefit to HIF [51].

At LBL, plans have been developed for a mid-sized accelerator which will increase the peak beam power available from the MBE-4 by roughly a factor of 1000. Called ILSE, for Induction Linac System Experiment, it is designed to complete the accelerator phase of the DOE program and allow decisions to be made regarding a fusion program based on induction accelerators for HIF [52]. Included in the ILSE plan are experiments on the transition from electrostatic to magnetic focusing of multiple beams, acceleration and pulse compression of the beams, bending of high-current beams, and drift-compression and final focus of one beam. A schematic of ILSE is shown in Fig. 1.

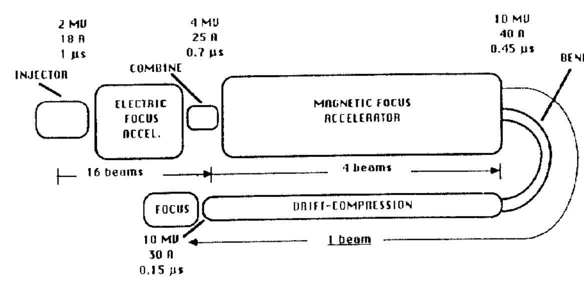

Fig. 1. Schematic of the Induction Linac System Experiment proposed by LBL [Ref. 52].

Other important HIF research activities are beyond the scope of this review. Topics omitted include final beam focusing, atomic physics, beam-plasma interactions, energy deposition in target materials, and system studies. We have limited our attention to accelerator research, with special reference to research having interest beyond HIF. Moreover, since time was not available to review the most recent work, interested readers may wish to refer to papers by many of the authors cited which are included elsewhere in these Proceedings.

I conclude with a quote from J.D. Lawson [53]: "Looking back over the first ten years it is apparent that much progress has been made towards understanding the requirements for a fusion reactor based on HIF. . . Clearly there is scope for many individual judgments concerning the ultimate feasibility of heavy ion fusion, and the part it might play in meeting our energy needs. It is also clear, ten years later, that the 'considerable enthusiam' referred to in the 1976 [summer study] is still very much in evidence."

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