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ACCELERATION SYSTEMS FOR HEAVY-ION BEAMS FOR INERTIAL CONFINEMENT FUSION

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1. Introduction

Heavy-ion beam pulse parameters needed to achieve useful electric power generation through inertial confinement fusion have been set forth by Nuckolls[1]. For successful ignition of a high-gain D-T target a few megajoules of energy per pulse, delivered at a peak power of several hundred terawatts, are needed; it must be deposited with an energy density of 20-30 megajoules per gram of the target material on which it impinges. Additional requirements must be met if this form of fusion is to be used for practical power generation; for example the igniter system for a 1 GWe power plant should have a repetition rate in the neighborhood of 1 - 10 Hz, an overall electrical conversion efficiency from mains to beam of greater than 10%, and high availability. At present under discussion are the needs for a Heavy-Ion Demonstration Experiment (HIDE); an example set of parameters is given in Table 1 for comparison with those for a power plant.

Many of these requirements either are not new to accelerator designers or are believed to be tractable. Synchrotrons and linacs have been run with repetition rates of many hertz. Particle beams with stored energy of 1 MJ exist at the FNAL and CERN synchrotrons; the stored energy per beam at the CERN-ISR is 4 MJ (and the power 1 TW), but these are light particles (protons) at high voltage (30 GV) and this experience is not directly applicable to heavy ions. Also, there is considerable engineering design and construction experience with accelerating systems several kilometers in length - the scale needed for a power plant. The SLAC accelerator is 3 km long and the FNAL synchrotron and associated transport lines exceed 10 km. The need for technical components with a total length measured in kilometers is not unique to the high-energy heavy-ion approach; it is also true of relativistic electron beam (REB) and laser igniters.

The new features of greatest concern to the high-energy accelerator physicist are the demand for a very large number of heavy ions -- two orders of magnitude more than present experience -- and the large final beam power. Together these lead to the most difficult problems of handling both transverse and longitudinal space-charge forces. In passing we also note (see Table I) that HIDE, while calling for a presently achievable number of ions per pulse, demands a peak power not very much less than for a power plant corresponding to an uncomfortably short pulse duration (2 nsec) at the final focus.

Table I: Parameter List

	1 GWe Power Plant	HIDE
Target Requirements		
Pulse Energy and Rate	10 MJ at ~ 1 Hz 1 MJ at ~ 10 Hz	0.1 MJ, very low rate
Peak Power in Pulse	100 - 600 TW	50 TW
Number of Beams	$\geqslant 2$	$\geqslant 2$
Example Accelerator Parameters (for ions with A ~ 240, charge qe)		
Ion Kinetic Energy	40 GeV	25 GeV
Number of Ions/Pulse	$\sim 10^{15}$	2.5×10^{13}
Pulse Rate	~1 Hz	very low
Target Spot Radius	~1 mm	~1 mm
Electrical Efficiency	$\geqslant$ 10%	very low
Peak Pulse Current	~ 10 q kA	2 q kA

2. Accelerator Systems

2.1 Choices: We can categorize systems being considered by the type of accelerator used to supply the bulk of the kinetic energy to the ions. Thus the three systems being studied can be broadly labelled (a) synchrotron (b) rf linac (c) induction linac. The first two systems are well-understood tools of high energy physics with a history dating back thirty years and have also been used to accelerate heavy ions for nuclear physics, e.g. the Unilac rf linac at Darmstadt and the Bevalac (rf linac and synchrotron) at Berkeley. In both cases it is envisioned that after acceleration the particles are loaded into a number of storage rings where they are later bunched and delivered as a number of individual simultaneous beams to the target. The induction linac is a non-cyclic non-resonant device made up of a large number of pulse-power voltage modules in series, each module having a modest stored energy. Only a few operating accelerators of this type exist in the U.S. and U.S.S.R.; they are used to accelerate electron beams in the 1 - 100 kA range to modest voltages ($\approx$ 10 MeV). Because of its capability to accelerate a high-current pulse of short duration such a system offers the attractive possibility of acting also as a buncher, thus avoiding a multiplicity of storage rings at the end of the accelerator. It should be noted that study of each of these three accelerating technologies can be of overall benefit; to give one example, a "synchrotron system" will need an rf linac of significant size as injector and may require use of the induction linac technology in the final beam-bunching stage.

2.2 Limits: It was emphasized earlier that the large particle number (or high beam current) and high final beam power are the novel elements which, taken together with the multiplicity of choices for ion mass A and charge state q and the spectrum of possibilities allowed by the target designers, make optimization among the many workable accelerator systems less than transparent at this stage. The problem of high final power will be discussed in a later section (2.4). At this point the transverse space-charge limits are addressed. In a long, straight transport system of quadrupole lenses there is a practical upper limit to the current that can be transported which is set by the need for the magnetic restoring force to exceed the defocusing electric self-field of the beam. This limit was first pointed out by Maschke[2] and because of its importance is the object of intensive recent and continuing study[3]. This limit can be written approximately as

$$I \leqslant I_T = C \left(\frac{q}{A}\right)^{2/3} \left(\frac{\eta B \varepsilon_N}{\sin\mu}\right)^{2/3} (\beta\gamma)^{5/3} \text{ amp}$$

where B = magnetic field at the edge of the beam (tesla); η = fraction of channel occupied by magnets; $\pi\varepsilon_N$ = normalized phase-space area of the beam (radian-meter); A, q = atomic weight and charge-state respectively of the ion species; and μ = betatron phase-shift per cell. It is not known how much depression of phase-shift by the space-charge is allowable; a value of $\mu \gtrsim 30°$ may be required because of nonlinearities. The value of the coefficient C is believed to be in the region of a few times 10^6 and will be controlled by the need to avoid beam-envelope instabilities of the type recently studied by Smith and Laslett[4]. Practical values for B are $\approx$ 1 T for conventional and $\approx$ 5 T for superconducting quadrupoles.

In a circular machine of mean radius R (e.g. synchrotron or storage ring) in which the particles make many revolutions the space charge limiting current is

$$I_C = 32 \times 10^6 \left(\frac{A}{q}\right) \frac{\Delta\nu}{R} \; \varepsilon_N \beta^2 \gamma^2 \text{ b amp}$$

where the bunching factor b is the fraction of the circumference occupied by particles, and $\Delta\nu$, the maximum permissible betatron tune shift, is usually taken to be 0.25. (It has been shown that this limit may be exceeded for a few turns during a transient longitudinal implosion of the bunch[5].)

2.3 Comparison of Systems: These space-charge limits enter in different ways in the various accelerator systems examined. One feature common to all, however, is the problem of handling the high current (~10 kA) in the final transport to the target (assuming one cannot use charge neutralization). Given the pole-tip field limit for superconducting magnets, and the desire to keep the number of final beams small, one is pushed in the direction of higher kinetic energy for the beam particles. This has the undesirable consequence, however, of calling for a smaller target size and higher brightness in the beam, for the same specific energy (MJ/gm).

In the case of a full-energy rf linac feeding a number of storage rings, space charge effects are uncomfortable during acceleration only in a short section at the front end of the accelerator. In this case the

current limit is in fact made less than that given above because of extra defocusing introduced by the rf field and effects due to the transit time factor. These problems may be relieved by using a number of low velocity accelerators in parallel and combining their output into a single beam at a velocity comfortably clear of the space-charge limit. Thereafter, since the current remains constant during acceleration, space charge is no longer an important consideration. At full energy the beam will be stacked in the storage rings and thus their design and configuration depend critically on the limit I_C.

A synchrotron system requires an rf linac as an injector and similar remarks apply to the low-velocity section of the injector. Likewise, space-charge limits are encountered in the storage rings at the full energy. In addition, however, the space charge limit I_C will be controlling at the time of injection into the synchrotron. If after acceleration further bunching within the synchrotron is desired it is possible that I_C will also be encountered there at full energy.

In the case of the induction linac the design of the machine depends strongly upon having a good understanding of the space charge limit I_T. In a broad sense the desire is to remain close to the transverse space-charge limit for as much of the length of the accelerator as possible. The current is amplified and the pulse duration shortened during acceleration by arranging for the applied voltages to have a slight positive ramp. Depending on exactly how the current is designed to increase as the particle bunch passes down the machine, the magnet transport system can be tailored -- in pole-tip field, spacing, and aperture -- so that the beam current remains close to the space charge limited current I_T at any point along the accelerator. The accelerating modules become undesirably bulky if the beam pulse duration is more that 1 or 2 usec, which corresponds to a beam current of hundreds of amperes. Thus an unusual injector must be provided to supply such a high-current initial beam pulse. A non-resonant drift tube structure -- relying also on capacitor storage and pulse-power techniques -- is one solution for the injector; another is to use a low-energy accumulator ring charged by an rf linac of a few hundred MeV.

Finally, some relative advantages and disadvantages of these different systems can be briefly mentioned. Because the particles recirculate many times through the same rf system, the synchrotron can achieve a much greater particle energy gain per meter of structure than can a linac. This "gradient" (MeV/m) is an important element in the final cost analysis and for either of the linacs -- rf or induction -- it seems difficult to achieve a gradient much more than about 2q MeV/m, where q is the ion charge state. To exploit to the fullest the high-gradient feature of the synchrotron the injection energy should be as small a fraction as possible of the final energy; a value ≈ 0.03 is common for proton synchrotrons. This can lead to two difficulties. First, the space-charge limiting current is low at injection. Second, adiabatic damping of the beam size causes it to occupy only a small fraction of the accelerator aperture at full energy; at this time the pulsed magnetic field is a maximum and must be supplied in a volume much larger that that occupied by the beam. Rapidly-pulsed power supplies to provide the needed field energy can be a significant cost item.

Like the synchrotron, the rf linac has the advantage that there is considerable engineering and operational experience with large systems,

e.g, SLAC (3 km) and LAMPF (≈ 1 km). Also, since an rf cavity acts as a voltage step-up device the insulator can be located at a low voltage point. The usual advantage of being a high-Q device, however, seems much less important for the present application because the large amount of charge (≈1 mC) to be accelerated corresponds to prohibitively high stored energy in the cavity; substantial power flow through an amplifier from an outside energy source will be required.

The induction linac has the potential for providing a single-pass system; avoiding the multiple traversals inherent in a synchrotron or storage ring can be important in minimizing beam loss due to ion-gas or ion-ion charge-transfer interactions, and loss from the inefficiencies of beam manipulations. It exploits pulse-power technology with advantages well-known to many attendees at this conference, viz., relatively cheap capacitor-storage and spark-gap switches, and good electrical conversion efficiency. The reliability and cost of high-voltage insulators are also well-known problems that will influence the choice of key design parameters. Some points of contrast and comparison between induction linacs and more familiar pulse-power systems are discussed below.

2.4 Final Bunching: Because the target requirement farthest removed from present experience is for high power pulses of short duration, it is of interest to estimate the limits imposed by present technology on final longitudinal compression of a bunch after it has been accelerated by known types of accelerators. (These limits could be greatly eased by space charge neutralization within the bunch, a technique not yet developed for high-current heavy-ion beams.) A synchrotron or rf linac must feed a number of accumulator rings by multi-turn injection, while an induction linac can accelerate all the ions in a single bunch. In such a ring, or along a drift line, a bunch may be shortened by applying enough electric field to decelerate front ions and accelerate back ones relative to those at the center. Denoting the magnitude of the (path-averaged) difference in applied field from end to center by ΔE (Volt/m), the equilibrium bunch length $\bar{L}$ (for which applied and self fields are balanced) is of order

$$\bar{L} \sim k[(qeN)/(n\Delta E)]^{1/2} \text{ meter}$$

with qe the ion charge (Coul.), N the total number of ions needed on target, and n the number of rings or bunches; k is ~ 3×10^5 and depends primarily on the form of the longitudinal distribution of charge. Pulsed accelerating gaps like those in an induction linac may be ramped to give $\Delta E \sim 1$ MV/m along a line as the bunch passes. However, in a ring the field must be produced for many turns, requiring rf cavities operating at low frequencies and having very different voltage capability and beam-loading properties, which must share path length with the ring magnets; therefore the path-averaged ΔE will be very much smaller. Without consideration of the momentum compaction factor, in a ring of circumference C meters an rf system would have to produce a differential (end to center) voltage gain of C MV/m to hold the same charge in equilibrium in the same bunch length. For heavy ions in low charge states a large ring multiplicity n would be needed to "buy back" the relative deficiency in ΔE to hold the product $n\Delta E$ to the same value as that in a pulsed-gap linear system.

Qausi-equilibrium compression, however, is a poor strategy. It is much better to implode the bunch longitudinally, starting with a length

much longer than $\bar{L}$, and producing the largest possible implosion velocity. The bunch will behave like a highly non-linear spring, the kinetic energy of inward drift imparted by the ramped field gradually turning into potential energy of compression until the length reaches a minimum when it strikes the target. The maximum compression is attained if a constant large ΔE is applied over the whole path. (This is possible with a pulsed-gap line for pulse times as small as 10 nsec, but not with rf systems unless complicated harmonic switching schemes are invoked.) It can be shown that in this case, subject to some simplifying assumptions,

$$L_{min} \sim (\bar{L})^2/L_i$$

with L_i the bunch length before implosion starts. If ΔE is switched off when $L = L_s < L_{min}$ and the beam coasts inward thereafter, the compression attained is less than above by a factor $\sim(1 - (L_s - L_{min})/L_i)$. This shows that for the rings additional compression by pulsed gaps following extraction will probably be needed.

From these approximate relations, the final bunch length is not less than $\sim 9 \times 10^{10}(qeN)/(nL_i\Delta E)$. For the induction linac L_i will probably be ~ 20 m to give accelerator pulse durations < 200 nsec which allow the use of ferrite for much of its length. For a ring, $L_i \sim C/2$. Thus

$$L_{min}(\text{ring case})/L_{min}(\text{line}) \lesssim 40/(n\Delta V/\text{turn})$$

for the same total charge on target; here ΔV/turn is the end-to-center differential voltage gain in the ring in MV/turn.

3. Pulse-Power Technology: Induction Linac for Heavy Ions and the REB Approach:

An example of a possible pulsed induction accelerating module is illustrated in Fig. 1. A Marx generator charged to, say, 30 kV provides a 500 kV charging pulse to a pulse forming network (PFN) which can be switched by a high-voltage spark-gap at the required time. A quasi-static accelerating voltage appears on the gap while the opposing voltage is prevented from appearing to the beam by the rising flux in the ferromagnetic loading material and the geometry of the conductors. Ferromagnetic loading has the advantage of causing high load impedance. Suitable materials for different pulse lengths are: laminated iron (~1μsec), ferrite (~0.1 μsec), or none at all $\lesssim$ 0.01 μsec; in the last case the configuration becomes that of the so called "radial line". In addition, for long pulses (≈1 μsec) the PFN may, perhaps, not be needed. The stored energy per module is a few kilojoules, and some 10^4 modules will be needed for a power-plant igniter system. The general concept of such a module, and the stored energy, are not very different from that used for the ERA injector which operated for many millions of pulses with good reproducibility; in that instance the energy per module and the currents switched were intentionally kept low in the interests of reliability and longevity[6]. The required number of switches will exceed present experience, although there have been years of experience with the Astron injector which had a total of 550 module switches. This induction linac also has an excellent record of multi-hertz operation for several years with excellent pulse-to-pulse reproducibility[7].

An analogy between induction linac and REB technology can be illustrated in the following way. If a sequence of accelerating modules such as shown in Fig. 1 are threaded by a metallic conductor on axis then the individual module voltages add and the tip of the rod becomes a terminal with a voltage equal to the summed voltages. Such a system with five sequenced 250 kV modules was used to make a 1.25 MV high voltage terminal for the ERA injector field-emission source. The sequence of modules can be considered in this case as analogous to the sequence of stages in a Marx generator with the difference that the interstage coupling is inductive and not conductive. This leads to two important differences from the Marx generator -- the generator impedance is high (the wrong direction for REB's!) but the maximum stored energy that can be released if a (single) fault occurs is small, no more than the few kilojoules contained in a single stage. In this illustration, naturally, the insulation required between the high-voltage terminal and ground is exactly the same as if it were excited by a Marx generator.

The situation is changed, however, if the sequence of modules (now considered large) is threaded not by a solid conductor but by a charged particle beam. Then the summed voltage to ground never appears on a material surface and multi-gigavolt accelerating voltages are achieved without having to contend with insulator stresses greater than about 0.5 MV per insulator. Also, the stored energy released in an electrical fault remains still in the kilojoule range appropriate to a module while the accumulated energy is stored in the kinetic energy of the beam and in the event of mishap can be handled without disruptive damage by accelerator "abort" techniques.

At a recent panel-meeting on Pulse-Power Technology, G. Yonas reviewed some of the problems in meeting the needs for inertial confinement fusion, e.g. energy storage, pulse forming systems, and power concentration[8]. He concluded that storage -- as evidenced by the Aurora 5 MJ system -- was a solved problem, that PFN switch problems were soluble for a demonstration system but not yet so for a high repetition rate system, and that power concentration could be achieved by using a multiplicity (~50) of systems, together with magnetically insulated vacuum line coupling, to approach powers of 1 - 10 TW/cm^2 at a diode terminal. Serving on the same panel, C. Martin recognized that a suitable system would require many thousands of switches, and that alleviation of the switch system reliability and repetition rate problems drove one to the highest operating voltages to minimize the electrical charge transfer per switch. In addition, Martin indicated that high repetition rate from a material cathode with very high power-concentration could be a major difficulty.

How do these concerns translate to the high-energy heavy ion approach? A central consideration is that we are dealing with a particle mass 4×10^5 times greater than that of the electron and, through the range-energy relation, beam voltages in the range 10 - 100 GV can be contemplated -- an extreme realization of one of Martin's points; this leads to a reduction in charge to the order of 1 millicoulomb. This brings dramatic relief to the switch reliability, switch repetition rate and switch jitter problems and we believe all are soluble by an extension of the pulse-power fan-out system that was used on the ERA injector. Energy storage at the level of 30 MJ required for a 1 GWe power plant seems more tractable, in terms of serviceable failures, packaged in a multiplicity of

units of a few kilojoules apiece, rather than in larger sub-units.

Emphasized earlier in this paper was the difficulty of achieving adequate beam power. This is visualized as being overcome by the tandem stacking of elements leading to high voltage, rather than the parallel stacking of multiple low-voltage beams. The cumulative storage of energy in particle inertia rather than at the surface of a material diode seems to have practical advantages. In addition a new dimension of power concentration is added by the use of non-relativistic particles that can be bunched in realizable distances; this is not an option for relativistic electron beams. In this way power densities of several thousand TW/cm^2 can be achieved at the target.

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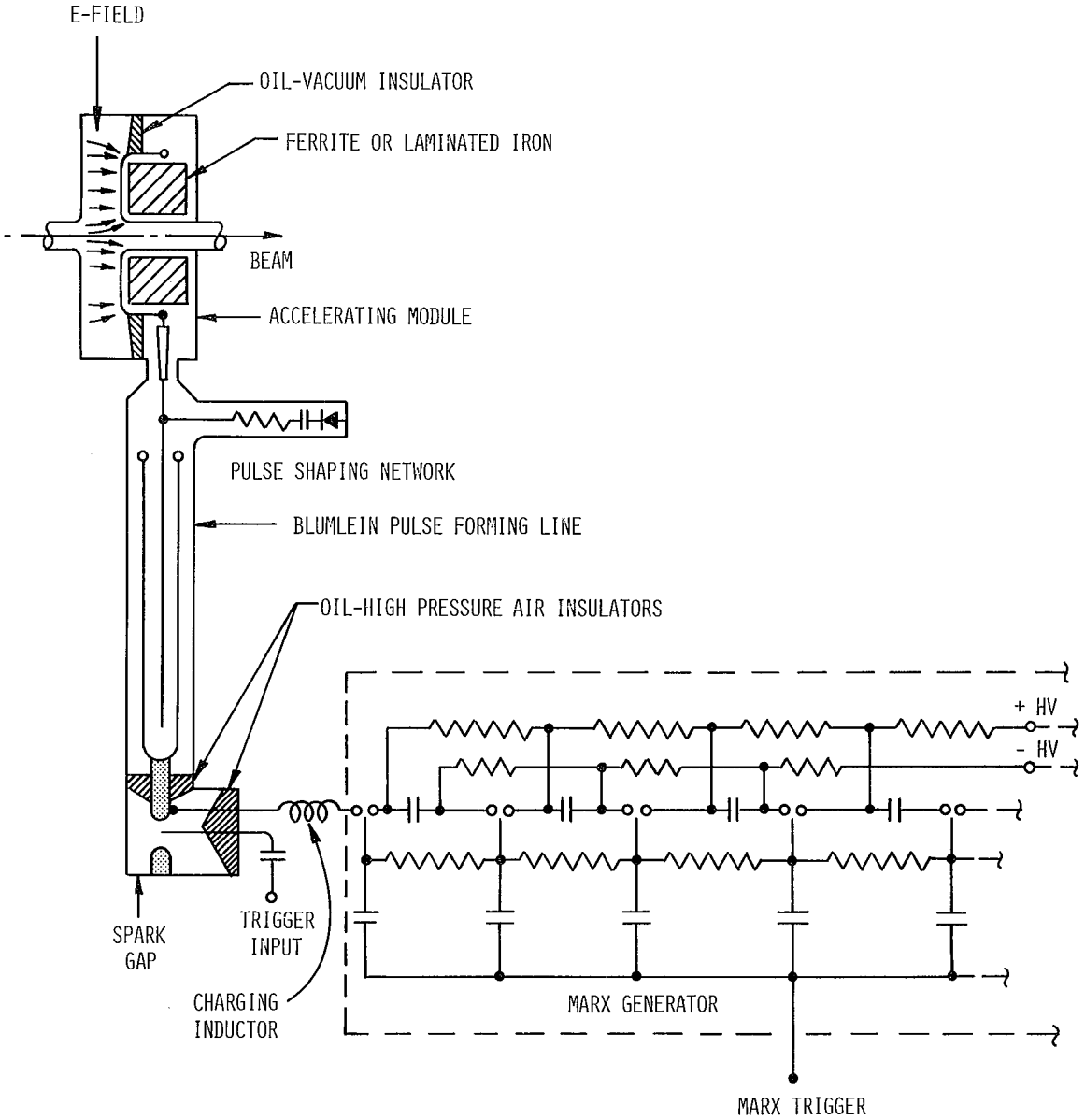

Figure 1

Representative Pulsed Induction Accelerator Module

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