BEAM DYNAMICS IN HEAVY ION FUSION

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Abstract

A standard design for heavy ion fusion drivers under study in the US. is an induction linac with electrostatic focusing at low energy and magnetic focusing at higher energy. The need to focus the intense beam to a few-millimeter size spot at the deuterium-tritium target establishes the emittance budget for the accelerator. Economic and technological considerations favor a larger number of beams in the low-energy, electrostatic-focusing section than in the high-energy, magnetic-focusing section. Combining four beams into a single focusing channel is a viable option, depending on the growth in emittance due to the combining process. Several significant beam dynamics issues that are, or have been, under active study are discussed: large space charge and image forces, beam wall clearances, halos, alignment, longitudinal instability, and bunch length control. .

I. HEAVY ION FUSION SYSTEM BASED ON INDUCTION LINEAR ACCELERATORS

A standard design for heavy ion fusion drivers under study in the U.S. is sketched in Fig. 1. An ion source and injector supplies 2-3 MeV beams to an electrostatically focused induction linac section (~64 beams). This is followed by a ~16 beam, magnetically focused induction linac section. The 64, later 16, beams are accelerated inside common induction cores. Finally, a compression section shortens the beams to a pulse length appropriate to the constraints of target ignition physics, and the last focusing elements bring the beams to a r=2-3 mm spot size.

Because the cost of the induction cores necessary for acceleration to 10 GeV is substantial, there is a premium on compact transverse packing of the parallel beams. Economic and technological considerations favor a larger number of beams in the low-energy, electrostatic-focusing section than in the high-energy, magnetic-focusing section. Combining four beams into a single focusing channel is a viable option, depending on the growth in emittance due to the combining process. (Other driver designs omit beam combining, and some of those use only electric or magnetic focusing, rather than both.)

RF based accelerator technology is the alternative principal heavy-ion driver approach. Storage rings are used for current multiplication, and it is there that the main challenges of beam dynamics are found. It is being studied in Europe, Russia, and Japan, and is discussed in ref. [1].

II. TARGET CONSTRAINTS ON THE DRIVER BEAM

We consider here indirect-drive targets[2], which have a frozen deuterium-tritium fuel shell inside a radiation enclosure, or hohlraum. The beam energy is deposited in converter material, and secondary, soft x-radiation propagates through the hohlraum, uniformly irradiating and imploding the fuel. Direct-drive targets are heated by the driver beams. In the latter situation, the illumination uniformity on the capsule is tightly coupled to the geometry of the incoming ion beams, and is generally considered to be a less conservative target design. Target design studies show that the driver must deposit ~400 TW for ~10 ns with a ~20 ns prepulse of <100 TW in order to achieve an energy gain of 10-100, or sufficient to make the economics work out favorably for commercial energy production.

Working backwards from ballistic transport with little or no neutralization leads to ~10 GeV kinetic energy with an ion atomic mass of 200. The target constraints establish an emittance budget in the transverse and longitudinal planes, approximately 6 π-mm-mrad and 1 eV-s, respectively.

Common to most variants of this 'standard' design are the assumptions of conservatively designed, conventional focusing systems throughout the driver. Another conservative assumption is ballistic transport of un-neutralized beams in the reactor chamber.

More exotic final focusing and chamber transport systems that rely on significant charge and current neutralization could make beam quality control easier. They are being investigated mainly for application near the end of the driver as a means for transporting the beams into the reactor chamber and to the target. Because these techniques are not applicable to most of the driver, much of the accelerator design would remain unchanged with a neutralized final focus at the end. However, the constraints on the number of beams, ion kinetic energy, and emittance could be relaxed. Fewer beams would simplify the interface between the driver and the reactor. The techniques, which are beyond the scope of this paper, include plasma lens focusing [3], and electron co-injection using a grid cathode [4].

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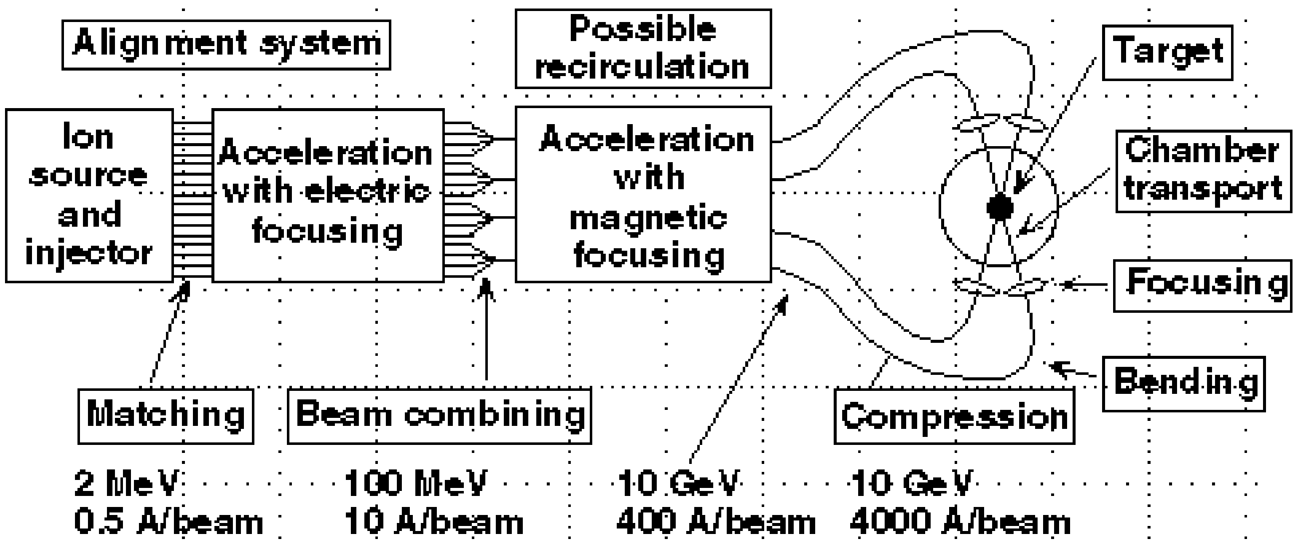

Figure 1: Block diagram of a heavy ion fusion driver. There are 64 beams in the electric focusing section, and 16 beams in the magnetic focusing section.

III. BEAM TRANSPORT

The characteristics of the beam in most of the driver are shown in table 1. The most current is transported when the space charge repulsion of the beam nearly balances the focusing force. The choice of σ_0 <90 deg avoids well established instabilities of highly space charge depressed beams for higher tunes. The line charge density is relatively uniform for most of the pulse and quickly drops to zero near the beam ends. Longitudinal repulsion at the ends is balanced by confining voltage pulses timed to coincide with the passage of the ends through the acceleration gaps.

σ_0	70-90 deg
σ	<20 deg.
λ_{Debye}	~1 mm
beam potential	~3 - 120 keV
λ (electric section)	0.20 - 0.30 μC/m
λ(magnetic section)	~1 μC/m at start 10 μC/m near end

Table 1: Beam characteristics in a heavy-ion fusion induction linear accelerator. σ_0 is the single particle tune, or phase advance per lattice period, σ is the space-charge depressed tune, and λ is the line charge density.

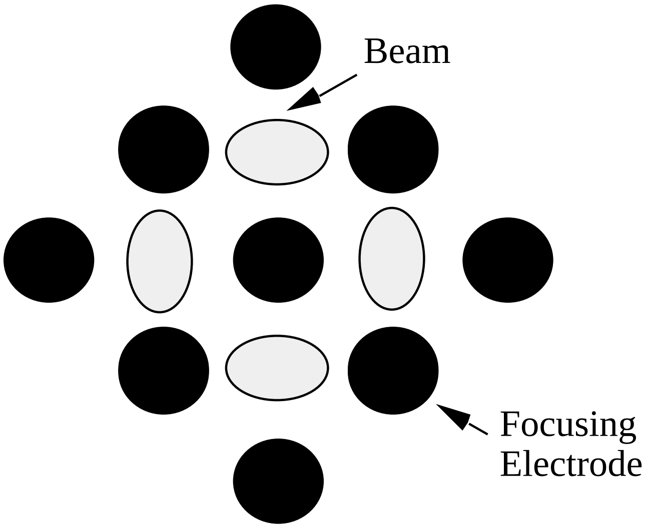

Figure 2: Schematic of part of a multiple beam electrostatic focusing array, showing the elliptical beams.

The electrostatically focused induction linac section has many parallel beams transported in a common induction linac core as shown in Fig. 2. Adjacent beams share electrodes and almost purely quadrupolar fields can be made from cylindrical electrodes inside much of the physical aperture by judiciously choosing the ratio of the diameter of the physical aperture to that of the electrodes. The docecapole component of the electric field can be eliminated with an 7/8 ratio. Because such electrostatic quadrupoles should be cheaper to fabricate than magnetic quadrupoles, and also because the focusing elements are closely spaced longitudinally at the low energy end of the accelerator, electric quadrupoles are favored over magnetic ones. The number of beams is determined by the high-voltage breakdown characteristics of the electric array and the need to transport a certain amount of charge in a pulse length that is initially ~30 μs long. The breakdown constraint in a multi-beam array should be that between adjacent electrodes of opposite polarity. Based on breakdown tests[5] of several electrode sizes and spacing (in the absence of beam), the estimated optimum is R_{ap}=2.3 cm, R_{el}=2.6 cm, Vq = ±70 kV. Unacceptable emittance growth from the non-linear image force occurs when the beam radius is >80% of the physical aperture. The beam-wall clearance should be increased by an additional 0.2 - 1 cm to accommodate mismatch oscillations that accumulate. They are caused by machining and alignment errors. Thus, with these clearance constraints, the maximum envelope radius in this part of the accelerator is 1.0 - 1.7 cm.

For higher velocity ions, magnetic focusing is stronger than electrostatic focusing. Since superconducting magnets would be economical, the additional space required for insulation and coils lead to an optimum with fewer beams and with larger transverse dimensions for the beams and quadrupoles. Another advantage of magnetic transport is that the maximum transportable line charge density is proportional to $B\beta a$, where B is the pole tip field, β is the relativistic factor, and a is the beam radius. Thus, for a constant beam radius, the pulse length may be reduced in proportion to increases in β, allowing the induction cores to be used more efficiently. System studies have shown that the transition from the electric section to the magnetic section with fewer beams should occur at 50-100 MeV. The electrostatically focused section is a few hundred meters long, and the magnetic section is several km long, with an average acceleration gradient of ~1 MV/m. The development of cost-effective beam sensing and steering systems to (infrequently) compensate for the machining and alignment imperfections would reduce the required beam clearance, lead to smaller quadrupoles, and decrease the required core material. The 16 beams in the magnetic section are consistent with the beam focusing constraints near the target and in the last focusing elements. Thus, the merging of beams into fewer transport channels is one of the main economically relevant beam manipulations in the driver, and it has critical beam dynamics issues that will be addressed below.

A slow growing longitudinal instability in induction linacs is due to longitudinal bunching of the beam. The seed for the instability may arise from an accelerating waveform imperfection. Then the perturbed distribution acts back on itself through the e.m.f. it induces in the induction cores, creating a growing wave backwards in the beam pulse rest frame. The growth rates are predicted to be greatest at frequencies below 30 MHz, but could be corrected by feed-forward control of the accelerating waveforms [6].

The beam pulse spans many lattice periods near the entrance to the electrostatically focussed accelerator (the lattice period is 0.45-0.6 m and the pulse length is ~25 m). Meanwhile, the increasing lattice period allows for an increase of λ by a few percent, and a corresponding small bunch compression. This implies that the acceleration gradient should be gentle enough so that the velocity variation along the bunch length at a fixed point in the lattice should be $\delta v/v < 0.2$. A higher initial gradient would introduce intolerable transverse mismatches for parts of the beam.

The increase in λ can be controlled by setting acceleration voltage waveforms to put a smooth head to tail velocity variation, or tilt on the bunch. Compression of the bunch by a factor of ~4 in the magnetic focusing part of the linac can be done in the same way. The final compression to the 10 ns pulse length (30 ns including the pre-pulse) occurs in a few hundred meters and requires a larger tilt. This part of the lattice is designed so that the longitudinal compression of the beam is overcome by the space charge repulsion at the capsule. This last compression occurs while the beams are bent towards the target, and achromatic designs have been developed to maintain the focal spot requirements, in the presence of the velocity and current variations of the bunch.

A variation on the linac design is one which includes a beam-recirculating induction linac. It potentially could reduce the cost of a driver by making use of the induction cores of the ring many times for each target shot. The induction core material would be reduced, and the total accelerator length would decrease. Unresolved beam dynamics issues in the recirculator are emittance growth and beam loss at injection and extraction and in the bends. The large space charge tune shift implies the crossing of many low-order resonances, but this is mitigated by the rapid variation of the betatron wavelength due to acceleration.

IV. MERGING OF BEAMS

Beam dynamics issues that are present throughout the accelerator are also important in designing a beam combiner: Space charge, image forces and aberrations of applied fields are critical in a lattice with little beam-to-wall clearance. Beam halo should be suppressed before the beam energy makes it an activation problem. The longitudinal velocity variation required for beam compression can be handled by designing an achromatic merging lattice. Another strategy would be to remove any tilt on the beam just before the combiner, and apply a tilt appropriate for the magnetic focusing lattice downstream.

Emittance growth and beam loss are the primary issues in determining the feasibility of merging beams which bears similarity to multi-turn injection in high energy physics storage rings. However, consideration of resonance crossing keeps the practical space charge tune shift lower in the storage ring case than in the situation described here. Experience with large contact ionization and alkali emitting alumno-silicate sources indicates that it is technically feasible to make a source and injector with a sufficiently high current density and transverse emittance limited mainly by the temperature of the emitting surface, or 0.15 π mm-mrad.

The contribution to emittance growth from space charge adds in quadrature to that from the geometric configuration of the beams at the merging point [7], or

$$\Delta\left(\varepsilon_n^2\right) = \left(\Delta\varepsilon_{sc}^2 + \Delta\varepsilon_{geom}^2\right) \quad ,$$

so the transverse phase space finally occupied by the merged beams is larger than what would be attributed to single particle dynamics filling in voids between beams ($\Delta\varepsilon_{geom}$). In a driver $\Delta\varepsilon_{geom} < \Delta\varepsilon_{sc}$ due to the large potential energy of the four-beam configuration that is converted into transverse thermal motion.

A critical issue for minimizing the emittance growth is the allowable clearance between the beam edge and the physical aperture. A substantial halo on the beam entering the combining hardware would necessitate a greater clearance between the beam and a septum of the combiner elements, and ultimately a greater emittance dilution downstream.

Beam loss in the merging process can occur directly by beam wall interactions in the combiner hardware, or via halo formation downstream. In either case it must be compensated by accelerating more charge initially. At 50-100 MeV, activation is not a concern but halo that forms after the combiner should be scraped before the particle kinetic energy reaches the Coulomb barrier.

The lattice elements of the combiner would need at least two dipole elements; one to displace the beams from the axes of their original transport channels and the second to aim the four beams onto a trajectory parallel to their common transport channel. The design of the last one or two elements is the most difficult, due to the spatial constraints and the desire to bring the beams close together. The envelope angles are largest when the beams are round, which is undesirable for the last element. The final element should bring the beams together when they are elliptical, and have relatively small envelope angles. A combined function dipole and quadrupole element appears feasible, by approximating the desired potential distribution at the beam boundaries by a large number of discrete conductors or electrodes.

In the case of an electrostatic combined function dipole-quadrupole element, the unwanted space charge and applied fields from neighboring beam channels can be effectively shielded by the conductors. Field and particle-in-cell simulations indicate that the beam edge to beam edge separation could be ~5 mm by using 1 mm diameter electrodes. On the other hand for a combiner to be used at the 50 MeV point of a driver, the difficulty presented by the high (~150 kV/cm) fields near the electrodes is serious.

A more tractable technical solution would be a (pulsed, warm) magnetic version of the combined function element. It would have peak fields of ~1.5 T, and field isolation between adjacent channels could be achieved with 1-2 mm of iron where adjacent beams are closest to one another.

A small scale beam combining experiment using entirely electrostatic focusing and dipole elements is underway at LBL [8].

V. OUTLOOK

After almost twenty years of theoretical and experimental research into heavy ion fusion with induction linacs, there are no dynamical problems that do not have a solution that fits into the driver scenario described here. Further work will help to weigh the merits among various design options. In all cases, the impact on the eventual cost of electricity will continue to be an important consideration.

At LBL, the ILSE accelerator [9] will be built to provide the beams that will enable testing many of the elements and manipulations of a fusion driver. Funding for the electric focusing section of ILSE (called Elise) has been approved, and a full engineering design will commence in 1995. The purpose of building ILSE is to explore the physics and engineering questions of the presently-conceived driver. The results will help determine and adjust the accelerator design. The ILSE beams will be equal to a driver in linear charge density, so a number of critical beam dynamics issues will be investigated at driver scale. However, to minimize cost, ILSE will have 10 MeV beams and fewer beams than a driver. It will consist of a 2 MeV, four beam injector, followed by an electrostatically focused matching section and induction linac. Each beam will initially have ~0.25 μC/m, and a bunch length of 1.5 μs. Except for bunch length and the number of beams, this part of ILSE is driver scale. The transition to the single-beam magnetic focusing section will occur at 5 MeV. A 4:1 beam combining experiment will be a central part of the ILSE experimental program. Drift compression, bending, and final focusing experiments will be carried out downstream of the 10 MeV point. A possible recirculation upgrade would increase the ion energy to ~100 MeV and address dynamics issues such as injection, extraction, and emittance growth due to bending.

VI. ACKNOWLEDGEMENTS

Discussions with Andy Faltens on various beam physics topics are gratefully acknowledged.

V. REFERENCES

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