THE MODULAR POINT DESIGN FOR HEAVY ION FUSION

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We report on an ongoing study on modular Heavy Ion Fusion drivers. The modular driver is characterized by 10 to 20 nearly identical induction linacs, each carrying a single high current beam. In this scheme, the Integrated Research Experiment (IRE) can be one of the full size induction linacs. Hence, this approach offers significant advantages in terms of driver development path. For beam transport, these modules use solenoids which are capable of carrying high line charge densities, even at low energies. A new injector concept allows compression of the beam to high line densities right at the source. The final drift compression is performed in a plasma, in which the large repulsive space charge effects are neutralized. Finally, the beam is transversely compressed onto the target, using either external solenoids or current-carrying channels (in the Assisted Pinch Mode of beam propagation). We will report on progress towards a self-consistent point design from injector to target. Considerations of driver architecture, chamber environment as well as the methodology for meeting target requirements of spot size, pulse shape and symmetry will also be described. Finally, some near-term experiments to address the key scientific issues will be discussed.

I. INTRODUCTION

The Robust Point Design (RPD) for a Heavy Ion Fusion power plant was completed in 2002[1]. The objective of the design study was to demonstrate the technical feasibility of a self-consistent point design from injector to target. The driver architecture was based on a multi-quadrupole transport system, with over 100 heavy ion beams within a single linear induction accelerator. While the study achieved its purpose of demonstrating technical feasibility, the final published design was not optimized economically. In addition, the development path associated with the RPD would require several stages and a correspondingly extended duration.

With the RPD as our technical baseline, we have proceeded in search of alternative concepts which may be more attractive from the point of view of cost and development path. The modular point design (MPD) concept has as its basis an architecture based on 20-40 independent and nearly identical modules. An Integrated Research Experiment (IRE) based on one of these modules will suffice as a technical demonstration of the full driver. The key elements of a single-beam IRE could in turn be demonstrated by a small-scale integrated experiment. The development path toward the final power plant is straightforward.

The cost benefits of such a driver are not intuitively obvious. As we shall see, the techniques we introduce are compatible with medium-weight ions with correspondingly lower kinetic energy on target. These accelerators are generally short (less than 1km). Furthermore, the transverse dimensions of each module are smaller than the RPD since each module transports a single beam rather than ~100 beams with associated quadrupoles. On the other hand, there are tens of modules in the MPD case, in contrast to a single accelerator in the RPD. Preliminary cost estimates indicate that the MPD could be quite competitive[2].

The new technical challenges are all associated with high line charge densities. This is not surprising, since we are considering fewer beams at lower kinetic energy, compared to the RPD, and the total energy required at target remains at around 6 or 7 MJ. Such high line charge densities are not compatible with RPD technologies, and new technical innovations must be introduced, from injector to target. In the remainder of this paper, we consider some of these innovations, and describe progress and research plans towards the ultimate goal of technical feasibility demonstration.

I.A. Solenoidal Transport

The induction linac approach is optimal when the beam current is high. The accelerator structure with induction cores has been the basis of the RPD and remains the basis for MPD. The RPD quadrupole transport system can accommodate high line charge at high kinetic energies, but limits transportable charge at low kinetic energies. This is in distinct contrast to the solenoidal scheme[3] where the transportable line charge density is independent of ion velocity. The line charge density (λ), transported in solenoidal channels of field strength B is given by

$$\lambda \approx \left(66\frac{\mu C}{m}\right)\left(\frac{B}{10T}\right)^2\left(\frac{\mathrm{a}}{10cm}\right)^2\left(\frac{20}{A/q}\right)\left(\frac{\eta}{1.0}\right)$$

where a is the beam radius and A/q is the ratio of atomic mass to charge state of the ion. h is the occupancy factor of the beamline (fraction of the beamline occupied by solenoidal magnets). Note that the beam velocity or kinetic energy does not appear in this formula. In addition, the lower the atomic number, the higher the line charge. This leads us to favor ions such as Ne. Such a driver will be short since the final kinetic energy is around 200 MeV.

Solenoids are not new, particularly to the induction accelerator community. In fact, the majority of existing induction linacs are based on solenoids. However, most of these machines are for intense relativistic electrons, and the required magnetic fields are much weaker (~kG). To test ion transport, we have planned a solenoidal transport experiment with tens of mA of K+ ions at 300 keV at the existing NTX facility. Four pulsed solenoids at 3T have been built and tested. In addition to experimental confirmation of the theoretical scaling, we will be studying the very important electron and gas effect, which impose severe constraints on all accelerators for intense beams. Solenoids are known to have beneficial effects for controlling wall-produced electrons. The overall effects on beam transport will be studied, and comparisons with quadrupole transport will be made.

While the efficacy of solenoids at low energies is a key feature we have used in the design of MPD, at high energies, quadrupoles can also be used for high line density transport. Thus, various hybrid transport schemes have also been considered.

I.B. Neutralized Drift Compression

In the RPD-type architectures, the beams are compressed longitudinally at accelerator exit by an order of magnitude in pulse length, in order to meet the target requirements on peak power and pulse shape. As the beam gets short, space charge effects become more severe. The perveance (the ratio between line density and the particle kinetic energy) places severe constraints on the charge per beam. In the MPD we consider beams with much higher perveance than the conventional schemes, due both to the higher line charge density, as well as the lower kinetic energy. Fundamentally new schemes for longitudinal compression must be invoked. The new element is Neutralized Drift Compression, where the beam is immersed in a neutralizing plasma through the entire process of beam compression.

While the idea is relatively new, it builds upon a body of knowledge in simulations and experiments of beams in plasma, accrued over the past few years in studies of neutralized final focusing. Neutralized transport is in fact a key component of the RPD and is founded upon very detailed simulations with LSP[4] and supported by experimental results from the NTX[5] program. The past studies concentrated on the transverse focusing of the beam by canceling the repulsive space charge forces. The new idea is simply an extension to include longitudinal space charge cancellation and beam compression.

Driver-scale simulations have been carried out with MPD-type beams. Very high line density Ne+1 beams were compressed over 100m distance to the required pulse length and spot size. See fig. 1

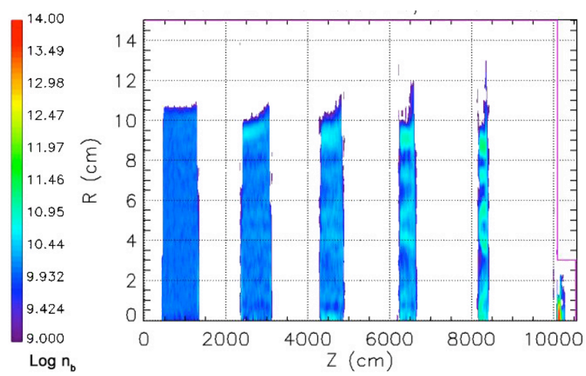

Figure 1: A 100-meter LSP Simulation of Neutralized Drift Compression for a Modular Drive

Necessary conditions are that the velocity tilt at the beginning of the Neutralized Drift Section be very well controlled, and that the longitudinal emittance be sufficiently small. In addition, the volume plasma must have adequate plasma, (10 times the beam density or greater) at all points in the Drift Compression section. The beams exhibit filamentation instability, which can be controlled to acceptable levels by imbedding the plasma in a weak solenoidal field.

A small-scale experiment is being assembled at LBNL as an extension of the NTX experiment. See fig. 2.

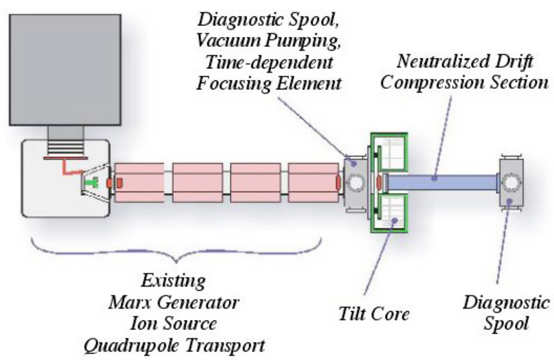

Figure 2: First Neutralized Drift Compression Experiment

The NDCX-I experiment has a modest goal of 10 fold compression, but will be extended to 100 fold in a follow-on experiment, NDCX-II.

I.C. High Line Density Injector

Conventional RPD-type injectors produce of order 0.25μC/m of heavy ions. Solenoids can transport line charge densities of two orders of magnitude greater. To make efficient use of the solenoids, the injector must produce comparably high line densities. Several concepts have been put forward, ranging from conventional sources with aggressive beam compression at the front end, to ion sources imbedded in plasma from birth.

The primary candidate for the injector at this point in time consists of an extension of conventional injectors. The idea is to produce and accelerate the ion beam from a large source (as in conventional guns), followed by immediate deceleration to low kinetic energy in a solenoidal channel. As the high energy ions are decelerated, the line density builds up. After the low energy ions are loaded completely into the solenoid channel, an electric field is applied to the entire beam, which is accelerated back up to higher energies, with the pulse length remaining fixed. This two-step process of "accel/decel", followed by "load and fire" leads to a high line density beam which can then be transported and accelerated in the main induction linac.

The beam dynamics as well as the implementation of this idea is nontrivial. We have planned a small-scale experiment to test this idea over the next two years. A full 3-D PIC simulation of this experiment has been completed, see fig. 3, although further optimization must be performed.

Figure 3: Simulation of a Scaled Experiment of a High Line Density Injector, Fully Self-Consistent WARP3D Calculation of an ACCEL-DECEL-LOAD-AND-FIRE SYSTEM.

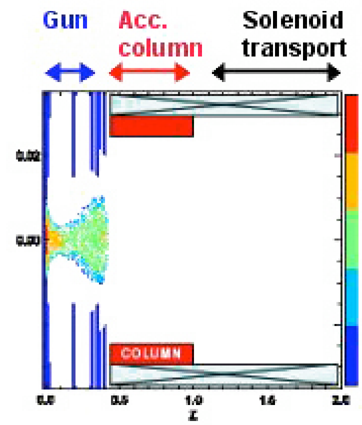

Figure 3a: Beam out of Gun

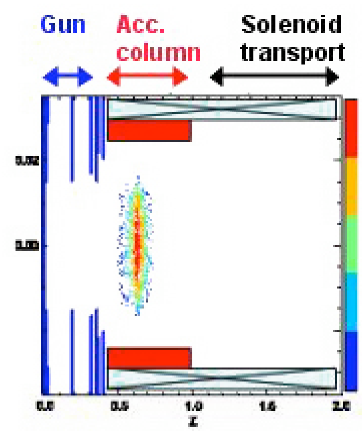

Figure 3b: Beam in Accelerating Column

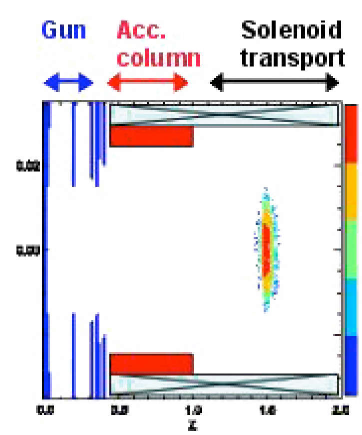

Figure 3c: Beam in Solenoid Transport

In addition, the basic concepts for the engineering design of this experiment are in place.

I.D. Hybrid Target

Significant progress has been reported on the hybrid target[6]. In contrast to the RPD, where the Distributed Radiator Target (DRT) was our baseline design, we choose the hybrid target as the baseline for the MPD. The major advantage of the hybrid target, from the point of view of the driver, is that it relaxes the focal spot radius requirement to ~5mm (in contrast to the DRT with its spot radius of ~2mm). This large focal spot size significantly relaxes the requirement on the driver and the final focus system.

The hybrid target, like the DRT, has pulse shape and symmetry requirements. It takes all 120 beams in the RPD to meet both requirements. The reason is that for the conventional drift compression in vacuum, there are large longitudinal space charge forces which prevent any attempt to separate very special pulse shapes required by the target. The pulse shape in the RPD was met by arranging blocks of beams with different timing. In contrast, the MPD beams see minimal space charge forces in the neutralized drift compression and final focus regions. The final current pulse shape is achieved simply by shaping the velocity profile at the entrance of neutralized drift. This is one big advantage associated with ballistic particle trajectories in the MPD.

On the other hand, whatever velocity imprint on the beam is "remembered" at the target. This is in contrast to the RPD where the space charge dominated beams are arranged to reach "stagnation" at final focus (a process by which space charge forces compensate for any initial velocity tilts to make the final energy constant from head to tail). A new requirement on the hybrid target in the MPD is that the velocity variations must be acceptable. For a given pulse shape, the magnitude of the velocity tilt can be changed with corresponding change in the length of the drift section. If the target can accommodate a large velocity tilt, then the drift section could be quite short, provided that the final focus system can accept the velocity tilt also.

I.E. Final Focus System and Chamber Concepts

At the present, two final focus systems are being pursued. Each final focus system is associated with a chamber concept.

The first system is solenoidal focusing with an associated new vortex chamber concept[7]. See fig. 4.

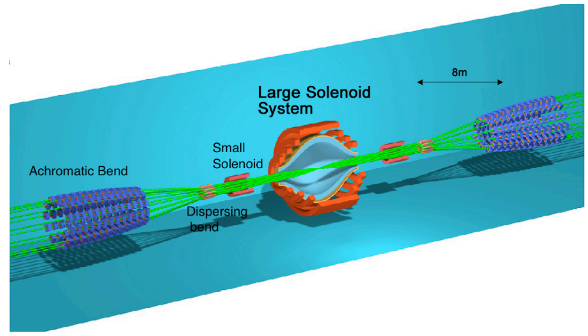

Figure 4: Solenoidal Final Focus and vortex chamber for a Modular driver

The vortex chamber is filled with a high density plasma and is protected by thick liquid Flibe vortices covering the entire chamber except the beam entrance ports on either end. The solenoids surround the chamber outside the walls. All beams from each side enter the chamber and are focused by the solenoids onto a 5mm spot at the target. The beams enter in an axis-symmetric array, assuring axis-symmetry on the target.

One of the key issues associated with this scheme is the dispersion due to the velocity tilt. Different beam components with different energies will have a slightly different focal length, thereby "smearing" the beam spot at target. A compensatory scheme has recently been constructed by Ed Lee[8] whereby dipoles introduced upstream of the chamber correct for the dispersion induced in the focusing solenoids. With this scheme, it was shown that beams with emittance of 100mm-mr and a velocity tilt of ±4% could be focused onto a 5mm radius spot. These calculations did not include the effects of the plasma, but are nevertheless very encouraging, provided that the plasma effects could be shown to be tolerable.

The second system consists of a tapered-wall "adiabatic lens" and a laser-initiated discharged channel from each side of a modified HYLIFE chamber. This so-called "Assisted Pinch" system has been studied in the context of RPD-like drivers[9]. Because this concept is designed to accommodate very high beam currents, it is well suited to the MPD architecture. The upstream end of the chamber consists of a solenoidal focusing system similar to the first case. In this scenario, the solenoidal focusing system is required to focus the beams to a ~1cm radius spot at the entrance to the adiabatic lens. The adiabatic lens and the discharge channel then take the combined beam and pinch the beam down to 5mm radius at target.

An integrated calculation was performed with LSP[10], which launched a beam from the exit of the solenoid accelerator, transitioned into a plasma-filled drift tube, compressed to ~10ns in a distance of 100 meters, focused by a solenoidal lens onto an adiabatic channel, and finally transported onto a hybrid target. This self-consistent calculation showed 92% delivery of the total energy onto a 5mm radius spot on the target. See fig. 5.

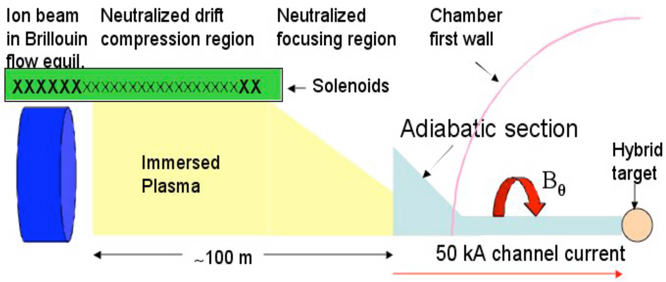

Figure 5: An integrated Assisted Pinch Simulation (LSP) from accelerator exit to target demonstrates 92% energy deposition within required 5mm spot

I.F. Modular Point Designs and High Energy Density Physics Applications

The 5 key elements for our modular point design are: beam injection acceleration and transport, drift compression, final focus and target. In addition to separately developing each of these elements, we are also attempting to put together a self-consistent point design, which is integrated from injector to target.

Recently, there is strong interest in High Energy Density Physics[11]. In particular, the region of Warm Dense Matter, at temperatures of 1 to 20 eV, involves the largely unexplored physics of strongly coupled plasma. Ion beams have significant advantages in accessing this region of physics. Near term accelerator concepts for HEDP share the same technical challenges. Hence our simulations and experiments will address HEDP and fusion in parallel.

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