

SCIENTIFIC ISSUES IN FUTURE INDUCTION LINAC ACCELERATORS FOR HEAVY ION FUSION*

C.M. CELATA

*Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA, 94720, U.S.A, and the Heavy
Ion Fusion Virtual National Laboratory*

Telephone: (510)486-7740 Fax: (510)486-5392 Email: CMCelata@lbl.gov

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The worldwide heavy ion fusion effort has made a large amount of progress over almost three decades of research on the intense beam physics and concepts needed for an inertial fusion driver. In the 1970's, '80's, and '90's in the U.S., most experiments used driver parameters scaled to low energy and low line charge density in order to study, most often with a single beam, the physics of high-perveance beams. More recently, the U.S. program has introduced higher line charge density experiments, where the beam space charge potential is significant. This allows investigation of the production, and effect on the beam, of stray electrons. Increasingly, the possibilities for neutralizing plasmas are also being investigated, both just upstream, and in, the target chamber. This talk will outline the scientific issues that remain to be examined. These include issues of longitudinal compression, dynamic aperture, electron/ion instabilities, effect of electrons and gas on the beam, longitudinal emittance evolution, halo production, inductive effects at high energy, multiple beams, innovative final focus approaches, and driver issues for solenoidal transport. An outline of future experiments to address these issues will be presented and discussed.

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1. Introduction

The scientific issues for induction linac drivers for Heavy Ion Fusion (HIF) all ultimately derive from the requirements for implosion set by target physics. Though there is a range of parameters given by different target designs, a representative set for indirect-drive targets would require 500 Terawatts of beam power, with beam pulse length of approximately 10 ns and range 0.02 - 0.2 g/cm² [1]. These basic requirements lead inevitably to certain design choices—in particular, the choice of parallel acceleration of multiple beams, since acceleration of the needed charge in a single beam is uneconomical and the emittance requirements to focus such a large beam to a spot of ~1-5 mm radius with the desired ~6 m focal length would be extremely hard to meet. The target also makes other demands on the beams—they must enter within a cone of half-angle $\leq 24^\circ$ (distributed radiator target), and there must be several sets at different energies, unless there is a method other than superposition to time-shape the pulses [2,3]. The main challenge, even in the multiple-beam case, is to transport beam perveance orders of magnitude higher than in conventional accelerators, with low enough emittance at the end to focus to the required beam spot size and pulse length. In 2001, a Science Workshop was held by the U.S. Heavy Ion Fusion community to examine the status and importance of the scientific issues involved in this task. This paper is a review and update of those issues, and an attempt to describe how the HIF Virtual National Laboratory (i.e., the HIF-VNL, a collaboration between heavy ion fusion groups at Lawrence Berkeley, Lawrence Livermore, and Princeton Plasma Physics National

Laboratories) program will address them. It will focus on science issues, leaving the extremely important area of technology for another author.

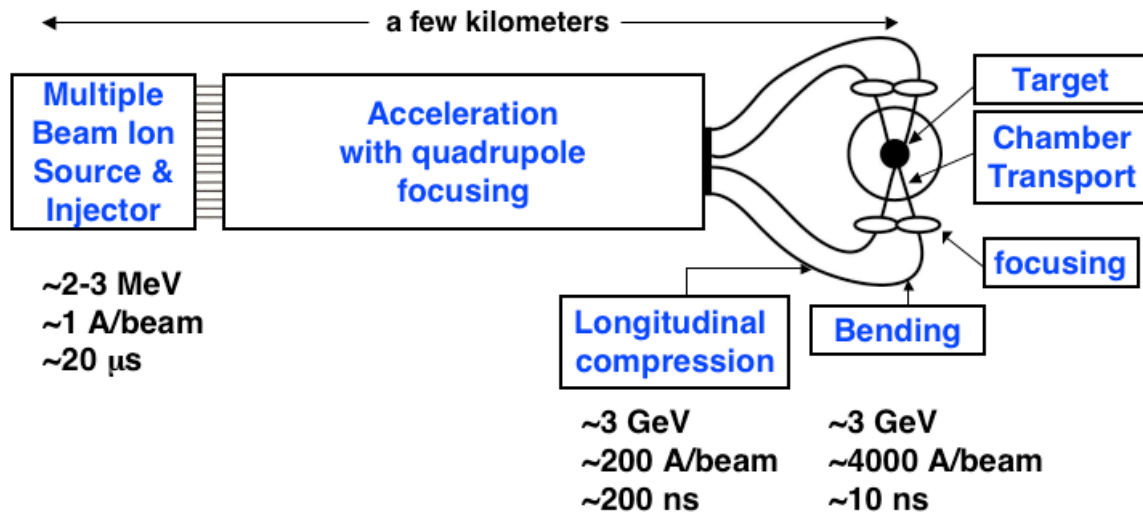


Figure 1. A schematic of a quadrupole-focused multibeam induction linac driver

The main constraint on the quality of the transport and acceleration required is the emittance necessary for final focus to a few-millimeter target spot. Assuming a final convergence angle of the beam envelope of ≈ 15 mrad as it leaves the final focus system (to avoid geometric aberrations induced by larger angles), this requires transverse normalized emittance less than approximately $10 \mu\text{m-mrad}$. The normalized emittance from the injector in present experiments is $\approx 1 \mu\text{m-mrad}$. Though this shows an order of magnitude leeway, it should be noted that target gain (energy out/energy in) increases with decreasing target size, and therefore with decreasing emittance, which gives an incentive to maintain the emittance below the maximum allowable value. Longitudinal emittance requirements are set by chromatic aberration limits in the final focus system to $\Delta p/p \approx 0.1\%-1\%$.

The mainline design for a HIF driver is shown in Fig. 1. This is a multibeam 3-GeV induction linac with ~ 100 beams of ~ 200 amu ions simultaneously accelerated in parallel, each beam in its own alternating-gradient quadrupole focusing channel. After the accelerator, the beams are longitudinally compressed by a factor of approximately 20 in the "drift compression" section, then each is focused by a several-quadrupole "final focus" section, and passes through a neutralizing plasma into the chamber, where it propagates to the target. The line charge density in the accelerator begins at about $0.25 \text{ } \mu\text{C/m}$, and compresses to about $1.5 \text{ } \mu\text{C/m}$ before drift compression. Beam current at the end of the drift compression is approximately 2 kA/beam.

In the past year, a new modular driver concept [4] has been examined which substitutes ~ 20 individual solenoid-focused lower-energy induction linacs for the conventional multibeam accelerator (Fig. 2). If it proves workable, this would provide a less expensive research development path to the driver (since only a single-beam lower-energy linac would need to be tested to show driver feasibility), and possibly a less expensive driver. The final velocity of the beams must be approximately that of the beams in the conventional driver in order to produce the same range in the target, and this is achieved in a present design by accelerating Ne^+ to a final energy of 200 MeV. The lower mass and lower number of beams (to minimize cost) require much higher current per beam after drift compression (~ 170 kA), in order to attain the correct total energy for the target. Present designs assume $\sim 2.5 \text{ } \mu\text{C/m}$ from the injector, compressing to approximately 10-30 times this value as soon as possible in the accelerator. Because of the extremely high charge per unit length (the single-beam perveance at the end of the accelerator is approximately 1500 times that of the conventional multibeam driver), final

drift compression can only be accomplished by neutralizing the beam. The neutralized beam must then be focused onto the target, perhaps using a plasma lens, large solenoid, or assisted pinch focusing. This new concept introduces many issues that were not considered at the 2001 workshop, which will be included below.

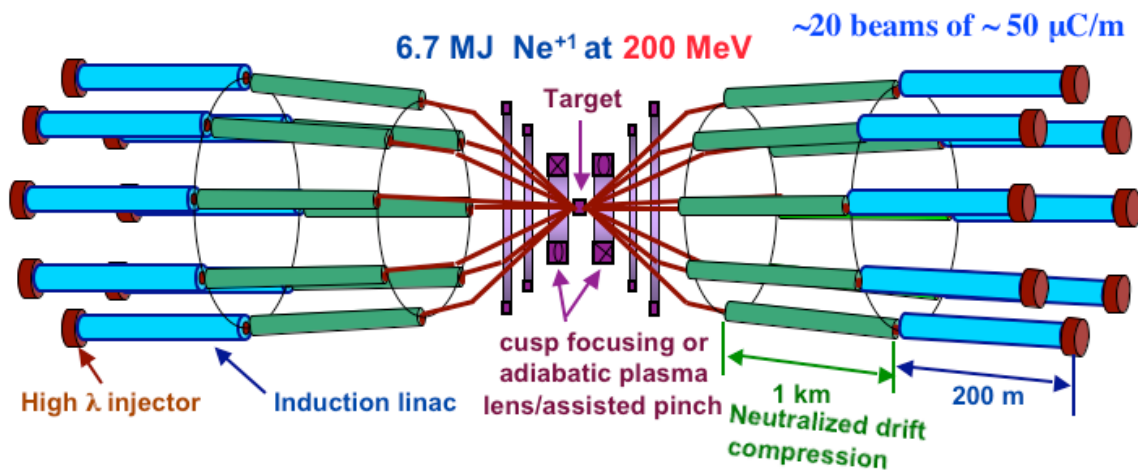


Figure 2. A conceptual drawing of a modular solenoid-focused driver

2. Scientific Issues and Their Status

A. Sources/Injectors

At the 2001 workshop, the U.S. community attempted to prioritize the long list of physics issues, large and small, which constituted all known questions for the quadrupole multibeam driver. In the source/injector area, the leading issue was the choice between the standard Pierce-diode solution for beam production and an idea for producing a compact injector for each beam which would form the beam by transversely merging perhaps ~ 100 very bright beams of smaller radius [5]. This choice has a large impact on driver front end size and cost, and perhaps even more of an impact on the cost of more

near term experiments. The choice of source was also given high priority—plasma and higher charge state sources were named as possible replacements for aluminosilicate “hotplate” sources. Other high-priority issues in this area were understanding of emittance growth and phase space changes in the injector, risetime requirements on the voltage pulse, nonuniform source emission, beam aperturing, capabilities of high-gradient insulators, and specifications for neutral emission from sources.

There has been significant, and in many cases definitive, progress in nearly every one of these areas in the past 3 years. In particular, there will soon be an experimental test of the multibeamlet injector concept (119 1.5-mA beamlets merged at 160 keV, then further accelerated to 400 keV in the injector column), which also includes high-gradient insulator tests. The main question for this idea is probably whether electrons and gas produced by the beamlets in the Einzel-lens acceleration section limit the pulse length. More fundamental work has also been done. The 500 kV STS-500 facility at LLNL has provided a test stand where comparison of theory and data on injector beam optics could be made, and there is extremely good agreement on both the phase space of the beam at the end of the injector, and, thanks to work on adaptive mesh refinement for the WARP PIC code [6], also on the current rise vs. time [7]. An argon plasma source was also tested at LLNL, and shown to have adequate performance (100 mA/cm² current density, >90% charge-state purity of Ar⁺, beam temperature < 2 eV, less than a few percent charge exchange) [8]. The 500 kV test stand has also provided understanding of nonuniform source emission and, with the High Current Experiment (HCX) [9] and the Neutralized Beam Experiment (NTX) [10], has begun investigation of the effects of aperturing. All of this work has shown that source and injector options for HIF drivers

exist and are nearly understood. Either the multibeamlet injector, if it proves viable, or the large aluminosilicate source with aperturing to remove aberrated beam, seems a good solution for a driver.

The latter choice points to one of the few remaining issues. Given the exciting progress in diode simulation, it is now possible to use computation to design in 3D a minimum-aberration large-aperture diode. This would be expected to greatly reduce the amount of beam that is thrown away by the aperturing process, and the solution would improve an essential element of many high-current accelerators.

Producing the high line charge density needed for the modular solenoid driver concept is a new challenge for the injector area. The present suggested solution is to decelerate charge at the end of the standard injector, using this “accel-decel” method to accumulate a large amount of charge, then accelerate all of it together in a “load and fire” scenario and further bunch in the accelerator. The accel-decel injector would bunch by a factor of ~ 10 . An experiment to investigate the limits of both the accel-decel and load-and-fire in a solenoid [11] will take place over the next few years using the NTX beamline.

Finally, while transverse phase space calculations compare extremely well with data, longitudinal dynamics in the injector has yet to be studied as thoroughly. Measuring the longitudinal phase space and understanding the workings of the temperature anisotropy instability in the injector will be important problems for both driver concepts, but perhaps especially for the accel-decel injector and modular solenoid approach, where more longitudinal bunching is required.

B. The Accelerator

Many issues were proposed at the Science Workshop as being high priority for the accelerator itself, and several more arise from the modular solenoid driver concept. For the accelerator it is difficult to get definitive answers to, or in some cases to even approach, many issues experimentally without a significant financial investment in new experiments. Most issues require a much longer lattice (≥ 50 lattice periods) than is available presently for intense ion beams, some only occur at high energy, and some require multiple beams.

Length scales for longitudinal dynamics are set by the propagation velocity of longitudinal waves, and the growth rate for the longitudinal instability. If the beam is in a transport system, with no influence of induction module capacitance, the wave velocity is approximately the sound speed, $(gK/2)^{1/2}$, where K is the dimensionless perveance and g is the longitudinal "g factor" ($g \approx \ln(b/a)$, where b is the vacuum pipe radius and a is the average beam radius-- typically $1 \ll g \ll 2$). From this, the waves can be seen to travel at speeds of a few mm/s at perveances characteristic of the high-energy end of a conventional driver, and a few cm/s at the low energy end. Of high interest is the observation of wave propagation in the beam ends, where wave speed slows. Thus an interesting experiment investigating wave propagation requires an accelerator of length a few tens of meters (e.g., ~ 50 lattice periods, or ~ 30 m). Damping and growth of the waves, however, take place over a much longer length scale [12], so that these phenomena would have to wait for an experiment hundreds of lattice periods long.

Transverse length scales again lead to consideration of an experiment with ~ 50 lattice periods and ~ 30 m. For typical beam and lattice parameters, 50 lattice periods

give about 15 plasma periods, 10 centroid oscillations, and 10 mismatch oscillation periods, though betatron oscillations are on a much longer scale (~ 1.4 oscillations in 30 m). Simulations also show that many transverse phenomena require this length (~ 50 lattice periods) for interesting experimental results.

Having given this general introduction of requirements, the high priority issues for the accelerator will now be discussed.

For the conventional driver, issues setting the limits to the usable aperture have high leverage for driver cost, and most were labeled as high priority at the 2001 workshop. The present VNL program focuses on these issues, including steering, mismatch, effects on the beam of gas and electrons, halo generation, and the effects of imperfect focusing fields and nonlinearities. In the electron/gas area, present experiments on the HCX can study the heart of the physics—production of electrons and gas and their orbital dynamics in the quadrupole and between quadrupoles and in induction gaps. This is a significant step. But measuring the effects of the electrons on beam transport, and their accumulation in the beam, must await longer experiments. Again, a 50-lattice period experiment would be a good beginning. In the meantime, the complicated several-species dynamics in this problem is being tackled computationally by adding new algorithms to the WARP code to enable it to handle widely divergent timescales. This work is advancing the state of “electron cloud” computations for both HIF and high energy and nuclear physics.

As mentioned above, longitudinal physics in the accelerator is also difficult to approach experimentally, given the long timescale of longitudinal wave motion, and especially growth and damping. As a result, little work has been done on this in recent

years. We have only estimates and some simulation to set bounds on longitudinal emittance growth, for instance, though some recent simulation studies have looked at the application of fields to contain the beam ends against space-charge expansion. These show the beam to be very tolerant of intermittent application of these fields. We know very little about the 3D dynamics in the beam ends, or about whether there is a 3D distribution function which is “natural” for beam transport in the way that uniform density is for transverse dynamics, i.e., resistant to change once produced. Such a result, should it exist, would set on solid ground the study of all drift compression and final focus dynamics, since simulations in that area could begin with a well-founded model for the beam distribution. These are rich areas for exploration with the UMER ring at University of Maryland [13] (path length of 11.5 m per turn, with 10 turns expected for high-tune-depression beams), or the Paul Trap Simulator Experiment [14] (ions trapped for ~ 100 ms, or effective path length ~ 7.5 km) at Princeton Plasma Physics Laboratory.

In one area, progress on longitudinal dynamics should be possible relatively soon. That is the transition of the beam from the injector to the accelerator. A single induction core on the HCX will be used to tailor the beam energy profile after the injector, including “catching” the space-charge expansion of the ends. This should correct the flattop energy to $\pm 0.1\%$. ± 200 kV solid-state “ear” correction pulsers will be used to regulate the control of the space-charge expansion of the beam ends with $\pm 3\%$ accuracy of the voltage waveform. The bandwidth of the system is 100 MHz. Simulations for IBX (Integrated Beam Experiment) [15-17] parameters have already predicted that this can be done with reasonable voltage waveforms while maintaining good beam quality .

Multiple beam effects require perhaps the greatest investment for experimental verification. Beam loading effects, including possible longitudinal instability, require high current and long length scales, and many multiple beam effects occur at high energies, where their inductive fields are important. For inductive fields to have comparable effect to electrostatic fields, assuming no shielding between beams, requires $N\beta^2 \sim 1$, where N =number of beams, and $\beta=v_{\text{beam}}/c$. This requires high energies for an ion beam: a 10-beam K^+ experiment, for instance, must reach 190 MeV energy to have $N\beta^2=0.1$. Thus these experiments will probably have to wait for a multibeam, 100's-of-MeV Integrated Research Experiment (IRE).

A solenoid-focused modular driver introduces many more issues [18]. Though solenoid transport is familiar from electron accelerators, the extremely high perveance, and space charge potential (e.g., 225 kV at the beam edge, for 25 $\mu\text{C}/\text{m}$ line charge density) of the ion beams, and the fact that they are nonrelativistic, puts dynamics for the HIF application in untested regimes. Every aspect needs to be simulated and verified experimentally, including mismatch, electron effects, effects of misalignment and focusing field errors, departures from Brillouin flow, etc.

C. Post-accelerator Issues: Drift Compression, Final Focus, Chamber Transport

Finally, the 2001 workshop considered post-accelerator issues—drift compression, final focus, and transport through the target chamber. Without listing even the highest priority issues, which are too numerous, it may be useful to make some general remarks on their extent.

The modular solenoid concept requires neutralized drift compression (NDC), while the conventional driver assumes unneutralized drift compression (UDC) so that conventional quadrupole focusing may be used in the final focus. Though essential for the mainline driver, unneutralized drift compression is perhaps the least explored of any part of the concept. Simulations are underway, and should explore such issues as the dependence on initial conditions, optimization of the lattice, midcourse corrections, sensitivity to errors, and emittance growth. Neutralized compression has received initial attention via simulation recently [19], and will be tested soon experimentally on the NTX. In both cases, sensitivity to the initial distribution function is important, since there is no experimental information on the state of the beam at the end of a long accelerator. Both NDC and UDC are difficult to test completely experimentally, but for different reasons. The issue for NDC is that this method has only been proposed for use when the perveance is too high for unneutralized compression, but it is an experiment in itself to produce the high perveance beams necessary (see above for injector tests). Unneutralized compression is expensive to test, since a few tens of meters of lattice are required, plus length and induction cores for preshaping of the pulse and applying the velocity “tilt” that compresses the beam. But it is important, once the simulation groundwork is laid, to field such an experiment, given its importance to the driver viability. Finally, it is worth noting that very little has been done, experimentally or computationally, on bending beams during drift compression.

The areas of final focus and chamber transport include a plethora of options at this point. The conventional multibeam driver assumes a standard quadrupole final focus section, followed by neutralization of each beam by plasma, then propagation through the

chamber, with its FLiBe vapor pressure [2]. Experiments on the quadrupole final focus system have been performed on the Scaled Final Focus Experiment [20] and on the NTX. So far, these experiments show that simulations can predict the beam behavior except for some halo, and emittance growth seems to be acceptable. Chromatic aberrations in the final focus produce a difficult tolerance of $\Delta p/p \approx 0.1-1\%$. Thus these aberrations, and aberration correction, are still major areas for investigation and improvement, and could have substantial impact.

The modular solenoid driver assumes a neutralized beam entering the final focus. Options for focusing then include plasma lenses, assisted pinch transport, and large solenoids. All of these will require simulation and experimental confirmation. Given the extremely high initial perveance of the beam (in present designs, about 1500 times that of the conventional driver, or $\sim 7.5 \times 10^{-2}$ after compression), an important consideration will be the extent and consistency of the neutralization as the beam compresses. Beam manipulations, errors, and transitions also pose issues. There have been small experiments [21] and quite a bit of simulation [22] of assisted pinch transport, but much remains to be done to extend this work to very high perveances and longer transport. It should be noted that if neutralized drift compression and these innovative final focus methods prove viable, they could be used also in the multibeam quadrupole drive, and would be likely to significantly ease emittance requirements.

Much progress has been made in simulating beam neutralization and chamber propagation, including ionization, stripping, and photoionization effects [23]. The NTX is presently acquiring data on neutralization [24], and we will know soon how well this is predicted by theory. At this stage, indications are that neutralization is workable and

robust—an important result for both driver concepts. Multiple beam effects and 3D effects, target charging and plasma blowoff, and the effect of FLiBe boundaries are important remaining questions for study in the chamber.

This paper will not cover target issues, except to note the large impact any loosening of beam requirements has for the driver. Robustness of the hybrid target, with its larger spot size, is important for both driver approaches, and possibly crucial for the modular solenoid driver. Testing of symmetry-stabilizing shims and other target features on the Z facility [25], and target experiments on the National Ignition Facility at LLNL will have very high leverage on driver design.

3. Priorities and Perspective

Though the above text gives a picture of the status of the science of Heavy Ion Fusion and the remaining issues, it might be useful to sort these issues in various ways. One obvious question is: which of these are feasibility issues? Feasibility issues are those that prevent the beam from reaching the target, or from focusing to the correct size or pulse length. From the above list then, for the conventional multibeam driver the following stand out: long-length-scale emittance growth from as-yet-unknown causes (no long experiments as yet), drift compression (neutralized and unneutralized), electrons/desorbed gas, and possibly the electrical effect of the FLiBe jets on the beams. There could also be multiple beam issues that should be included here, but no specific problems are anticipated. The first two issues in this list speak to emittance growth. Longitudinal emittance growth is a particular concern, because of the lack of

experimental results and the low acceptable level ($\Delta p/p \approx 0.1-1\%$, as mentioned above) for a quadrupole final focus system. In the case of neutralized drift compression, experiments will come in the next few years (though not with the simultaneous high perveance and high current of the driver), and simulations are in progress. But unneutralized drift compression experiments are not imminent, and simulation is complicated. Experiments have not provided the incoming distribution function, so the parameter space is large. The optimum pulse shape in z is not known. Multiple constraints are imposed by engineering limitations on induction core voltage waveforms, so the problem becomes a many-variable 3D simulation optimization problem, and the pulse-shaping section and tilt application must be included in the calculation. The problem is important and will take time, but given its importance it must be given priority.

Electrons effects produced by halo scraping, ionization by the beam of desorbed gas, or ionization of background gas are also serious issues, and again the computational problem is large and complicated. But there have been recent measurements that lead to some optimism. Measured coefficients for primary electron production by halo scraping and for desorbed gas production are in the range expected, and a simple, inexpensive method of mitigation (bead-blasting the vacuum wall) reduces the former by an order of magnitude and the latter by factors of 2-3 [26]. And simulations show that beam transport seems to tolerate more electron contamination than expected [27]. But much remains to be done, both experimentally and theoretically. Understanding halo production and scraping is the key to success here, and while aperturing experiments on both the NTX and the STS-500 appear to produce a good beam, all the data is not in. It

should be recognized that the effects of electrons and gas can always be mitigated by increasing the aperture, so that cost then becomes the issue, rather than feasibility.

The last issue concerns the possible effect of the FLiBe jets on the beams. They are placed asymmetrically about the beams, and can donate electrons for neutralization when photoionized, possibly leaving a strong electric field on the jet. This asymmetric effect could displace the beams' centroids.

To this list should be added many issues of feasibility for the modular solenoid driver. The concept is new, and investigation has just begun. Neutralized drift compression is essential for this concept, as is a final focus method (plasma lens, or solenoid, or assisted pinch) that can handle a coherent velocity tilt and perhaps a large velocity spread. And as indicated above, production, solenoid transport, and transitions for the extremely high perveance ion beams in this system have yet to be demonstrated, as well as compatibility with a qualified target. This is a fruitful area for simulation.

It is important to note, in ending this section, the comforting fact that the list of feasibility issues is short, at least for the conventional driver, and many are being tackled very productively at present.

4. Indicated Future Experiments

The experimental path indicated by the discussion above is, not surprisingly, the path that the program has been attempting to follow, subject to funding. In the short term, experiments on electron and gas dynamics, solenoid transport, neutralized drift compression, and accel-decel bunching are important and either planned or underway.

There is also currently a possibility, which should not be missed, of performing measurements on the electrical properties of FLiBe.

Given their importance, it is unfortunate that unneutralized drift compression experiments have been delayed. It will be important to extend or build an experiment to the length required, as a next experimental step. This longer lattice would also begin to reach the length necessary (~30 m, and 50 lattice periods, as discussed above) to check the influence of electrons on beam propagation, look at longitudinal wave propagation, and do better, longer experiments on halo production and scraping and fill factor limits, provided the lattice requirements can be made compatible with the drift compression. Along with this, long-transport studies, especially in the area of longitudinal dynamics, provided by UMER or the PTSX will add information unavailable soon in any other way. Once these longer transport and drift compression experiments are completed, a final focus section, with neutralization, could be added to the long transport/drift compression experiment, to produce the Integrated Beam Experiment (IBX). This could be a fairly low energy (~6-10 MeV) single beam experiment which nevertheless would be the necessary next step in integrating the beam manipulations and beam dynamics studies of all issues except those of long length scales, high energy, or multiple beams. These more difficult issues to reach require an Integrated Research Experiment (IRE), which would accelerate driver-scale beams to several hundred MeV. The IBX design could include and test elements of both the multibeam quadrupole and modular solenoid driver, but a choice between the two should be made before construction of the IRE.

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