Report from working group 3: multi-gap pulsed power

Alex Friedman and Richard Briggs

Introduction

This large working group discussed a wide range of topics, including a number of accelerator architectures that fall under the general heading of multi-gap pulsed power; general physics issues and constraints; and the interfaces to both injector systems and final compression/focusing systems. In addition, the group met with the Final Compression and Focusing group, organized a more detailed presentation by Craig Olson on the Ionization Front Accelerator (held jointly with the Experiments group), and enjoyed the participation of group members knowledgeable about single-gap diodes (a working group that had met separately, in advance of the main workshop).

This overview begins with a brief description of concepts for the injection of a beam with high line charge density. The approach currently being explored for near-term experimental tests on the NDCX facility at LBNL is the "accel-decel / load-and-fire" principle; a diode that uses magnetic insulation to forestall electron backflow across the gap is another possibility. Two accelerator concepts were examined in some detail. These were the Broad-Band Traveling Wave Accelerator (BBTWA) and the Drift Tube Linac (DTL). Two other approaches that have received recent study, the Multi-Pulse Induction Linac and the High-Gradient Induction Accelerator, were also considered in brief, but did not receive detailed examination during the workshop. This overview describes the first two of these approaches, and (more briefly) the latter two. Finally, a brief summary of a discussion on physics constraints is presented. The reader is referred to the summaries of many of these topics, to be found elsewhere in these Proceedings.

Injection at high line charge density

(Presentations were made by Enrique Henestroza and, as part of his plenary talk, Joe Kwan)

Two concepts for injection at high line charge density were presented during the opening day's talk by Joe Kwan: a magnetically-insulated short-pulse diode and the "accel-decel / load-and-fire" principle. An illustration of one possible configuration for a magnetically insulated diode is shown in Fig. AAA.

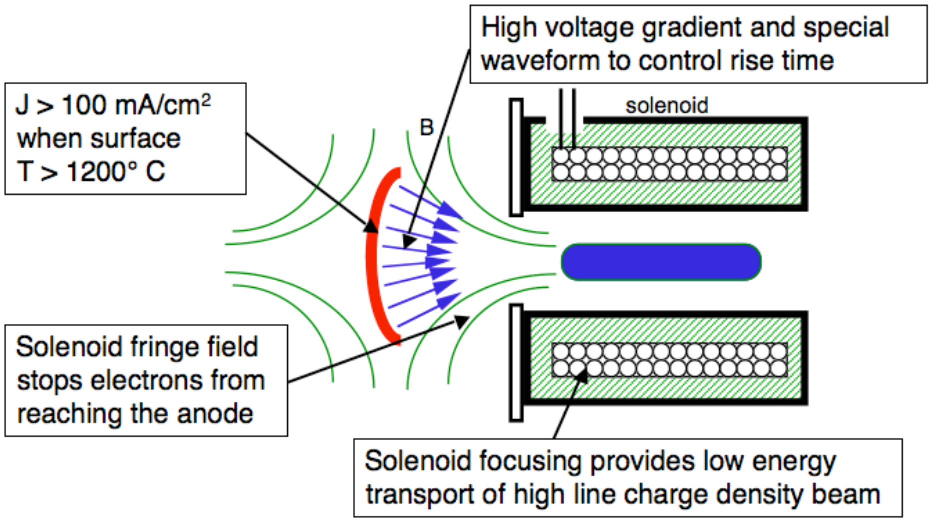


Fig. AAA. One concept for a short-gap diode employing magnetic insulation.

In the accel-decel / load-and-fire concept, a beam is accelerated in a high-voltage diode to obtain a large current; decelerated to a slow speed to obtain a high line charge density (in steady flow, the current is constant along the beam line); “loaded” into a solenoid; and finally “fired” downstream as a bunched beam, that is, accelerated all at once in a resistively graded column. A different load-and-fire approach, based on the helical-line traveling wave principle as described herein, was suggested at the workshop by Dick Briggs as an alternative worth analyzing in more detail. Additional analysis done after the close of the workshop proper indicates this option may have a number of advantages. By varying the waveform applied to the helix, a variety of initial pulse compression “tilts” may be imposed and tested experimentally, and more aggressive “early bunching” carried out.

The NDCX-1 experimental program at LBNL is intended to explore the physics of neutralized drift compression (in phase 1a, beginning concurrently with this writing), solenoid transport (1b, beginning in June of 2005), and accel-decel / load-and-fire injection (1c, beginning in October of 2005). The configuration of NDCX-1c as currently envisioned (it is still evolving) is shown schematically in Fig. AA, and a CAD rendering is shown in Fig. BB.

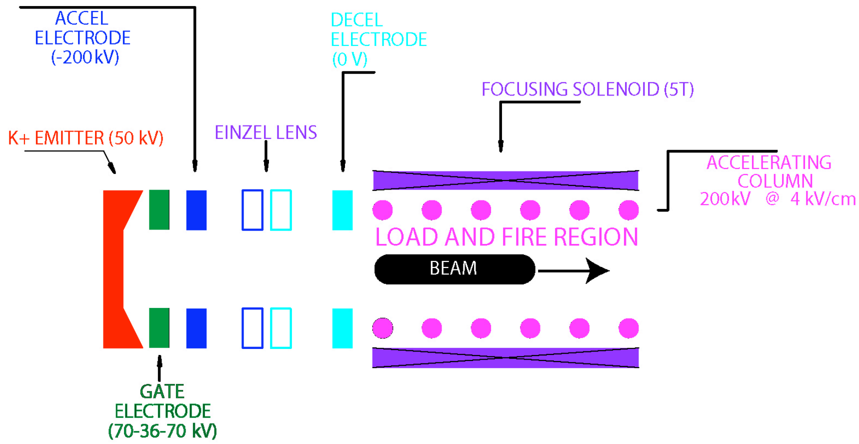


Fig. AA. Schematic of accel-decel / load-and-fire injector experiment on NDCX.

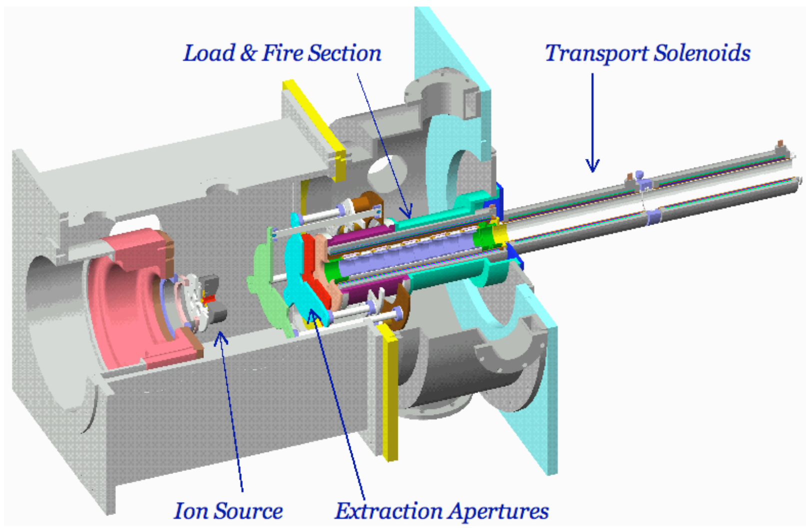


Fig. BB. CAD rendering of accel-decel / load-and-fire injector experiment on NDCX.

Simulations of the accel-decel / load-and-fire experiments are being carried out using WARP, and these were discussed during the working group's sessions. An example of such a simulation is shown in Fig.~CC.

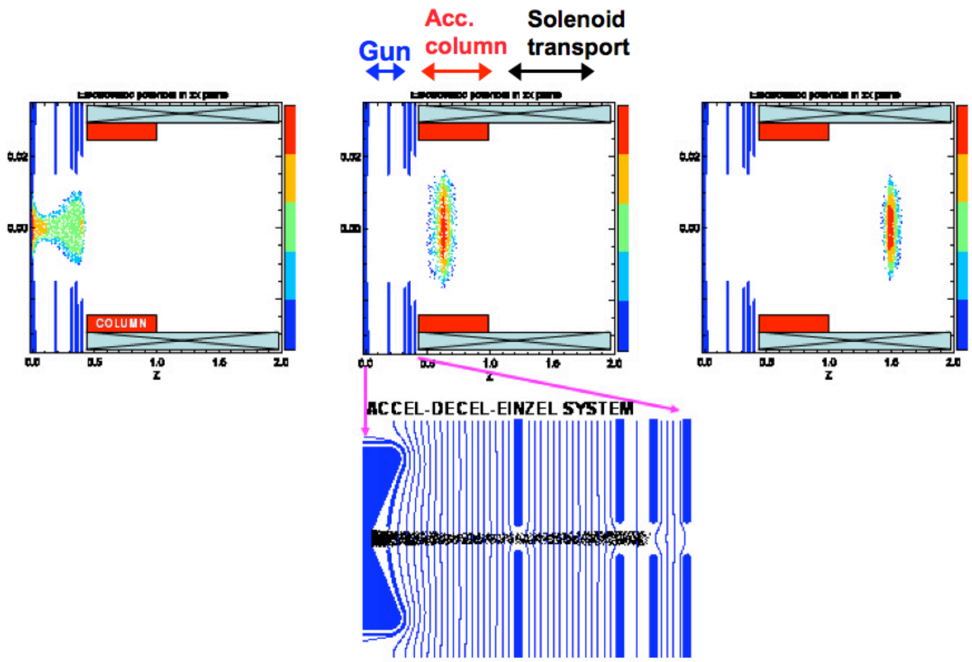


Fig. CC. WARP simulation of a possible NDCX-1c accel-decel/load-and-fire experiment

A topic of some concern to the working group was the question of how well matched transversely the beam head could be given that, in the ideal 1D case solved by Lampel-Tieffenback and independently by Caporaso, the beam head rises as a step function, so that particles at the head should experience half the transverse space charge defocusing force experienced by those in the body. Nonetheless, simulations indicate a well-behaved beam head. The resolution seems to be that the converging diode geometry and the unequal transit times of particles at different transverse positions conspire to generate a rounded beam head that is in approximate force balance. This is evident in the simulations, and can be seen in Fig. DD.

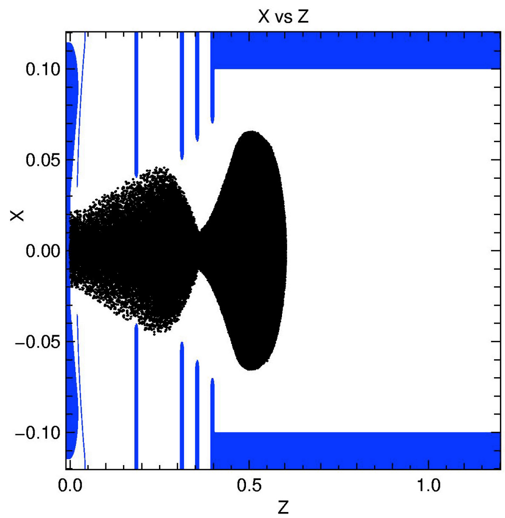


Fig. DD. WARPrz simulation of accel-decel process in possible NDCX-1c configuration with perveance Q ~ 0.05, 500 ns duration, 140 mA peak current, 50 keV K^+, 0.05 μC, showing benign behavior of beam head.

Informal goals for NDCX-1c are: Q = 0.05; I = 140 mA peak; beam energy after accel-decel 50 kV; K^+, λ = 1/4 μC/m; τ_{pulse} = 1/2 - 1 μs (q_{tot} = 0.05 - 0.1 μC). A resistive column 50 cm (5 T solenoid 60 cm) imparts (mostly) tilt; for the 200 kV column case, two cases were identified: (1) 180 keV head, 250 keV tail (1/2 μs , beam= 25 cm); (2) 50 keV head, 250 keV tail (1 μs , beam=50 cm).

Broad-Band Traveling Wave Accelerator concept

(Presentations were made by Dick Briggs, Scott Nelson, and Alex Friedman; the subgroup working on this topic consisted of Alex Friedman (chair), Dick Briggs, George Caporaso, Enrique Henestroza, Ned Birdsall, Will Waldron, and Yu-Jiuan Chen)

This concept is also referred to as a "Pulse-Line Ion Accelerator," as well as by other names. It is based upon the idea of launching a voltage pulse into a broad band slow-wave structure. If the line is sufficiently non-dispersive, a voltage pulse with a segment that rises linearly in time at the input end will become a linear ramp in space, corresponding to a region of constant accelerating field. The voltage pulse travels down the line with minimal deformation, and has the appearance of a solitary wave (though the governing equations of this system are linear). The beam pulse "surfs" on the traveling wave, experiencing a total energy gain that can greatly exceed the applied voltage. The current favorite for this slow-wave structure consists of a helical wire, inside a metal tube and embedded in dielectric material. The applied voltage waveform can be shaped so as to afford longitudinal confinement of the beam against its own space charge forces, and indeed to impart an inward compression to the beam in anticipation of neutralized drift compression. In the first stage, the pulse (and beam) may be moving as slowly as 1% of the speed of light.

A possible configuration is shown in Fig. EE, and one possible layout for an HEDP facility based on this principle is shown in Fig. FF.

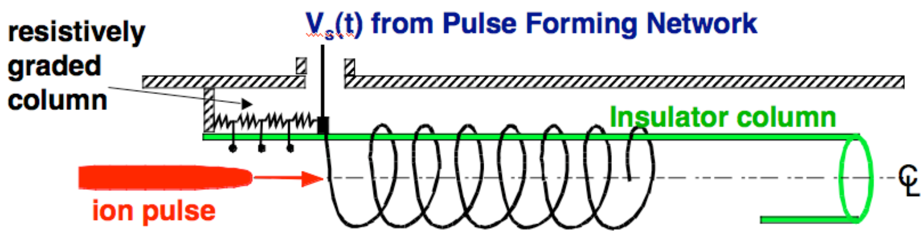


Fig. EE. A possible configuration for a Pulse Line Ion Accelerator.

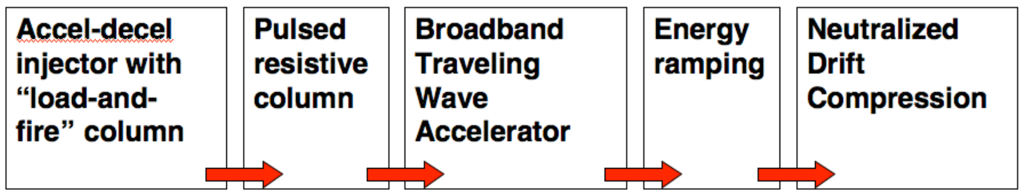


Fig. FF. One layout for a Pulse Line Ion Accelerator HEDP facility.

Success on NDCX-1 and on BBTWA helix tests now under way would offer a new opportunity for the NDCX-2 experiments, planned for the 2009 time-frame, to heat matter significantly. A BBTWA might be appended to NDCX-1, which could continue to use K^+ or could use Na^+, instead of the He^+ considered for the induction-based nominal "reference design" HEDP/WDM user facility. The final energy of 20 MeV is less than that of the Bragg peak (~50 MeV), but the energy deposition at that lower energy is only down by 10-15%. Target heating to ~1 eV is estimated, for a focal spot radius less than but of order a millimeter.

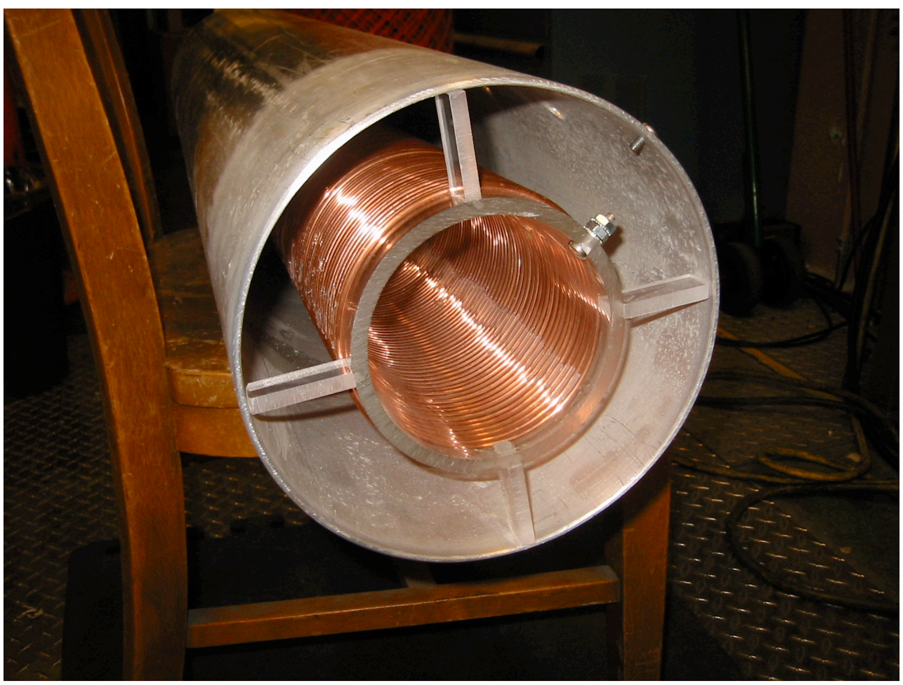
Such a system might use three segments of helix, each with a "tapered" line designed to track a factor-of-two gain in velocity. Other parameters are: $r_{beam} = 2$ cm, $a_{helix} = 4$ cm, $b_{wall} = 10$ cm, +/-450 kV drive (not all usable for beam), $l_{beam} = 15$-20 cm, voltage ramp over 30 cm (implying acceleration at 3 MV/m). Note that the voltage waveform can impart "tilt" in the helix (in addition to any imparted by the upstream system); longitudinal space-charge blow-up is controlled by this "tilt" as well as by "inertia" (the rapid acceleration implies a short residence time). The system would be ~3 m long, and the cost appears to be attractive; helices are inexpensive, and commercial solenoids are available at ~ $2M for a 5-T system of the required length.

For the "reference" HEDP facility itself that would follow, one possibility is a 20 MeV Ne^+ beam with total charge of 1 μC, in a parabolic-profile bunch with length constant at 30 cm, and a peak line charge density of 5 μC/m. The beam radius would be 3 cm, and 9-T solenoids would afford transverse confinement. The helix radius would be 6 cm, leading to peak voltages of +/- 750 KV, and a peak radial stress of 125 KV/cm in a bore tube of diameter 30 cm. The peak axial space charge field would be +/-0.8 MV/m, and the acceleration gradient (and vacuum stress along the insulator column) 5 MV/m.

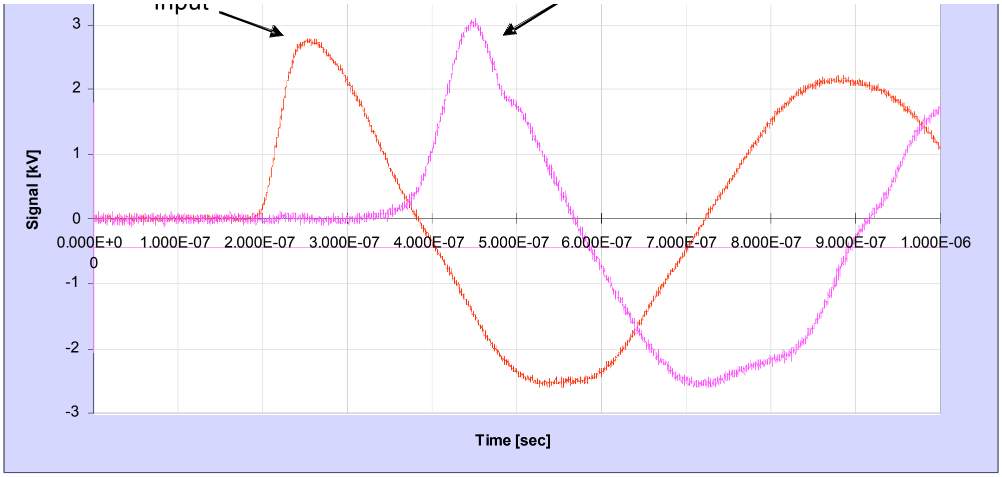
Several final bunch compression and focusing options can be considered for a Pulse Line Ion Accelerator based system. In such a system, the final tilt is imposed by the last helix segment; the 30-cm pulse implies a short neutralized drift compression section a few meters in length. The perveance at the 20 MeV output end is of order $2x10^{-3}$. Three options (roughly in increasing order of aggressiveness) are: (1) Helix -> Strong Solenoids -> Dipole -> Stripper to +7 -> Neutralized Drift Compression (NDC) at 1 T (match from ~3 cm to ~1 cm radius for NDC) -> 15 T Solenoid -> Target; (2) Helix -> Dipole -> Optional Stripper -> Graded-solenoid NDC (beam radius reduced gradually during NDC, no matching section) -> 15 T Solenoid -> Target; and (3) Helix -> Graded-solenoid NDC (plasma builds up along line, gradually) -> 15 T Solenoid -> Target.

Both experimental and theoretical / simulation studies of helical-line ion acceleration principles are underway. Low voltage models have been constructed to test the propagation of ramped pulses, and to measure the dispersion in the frequency domain.

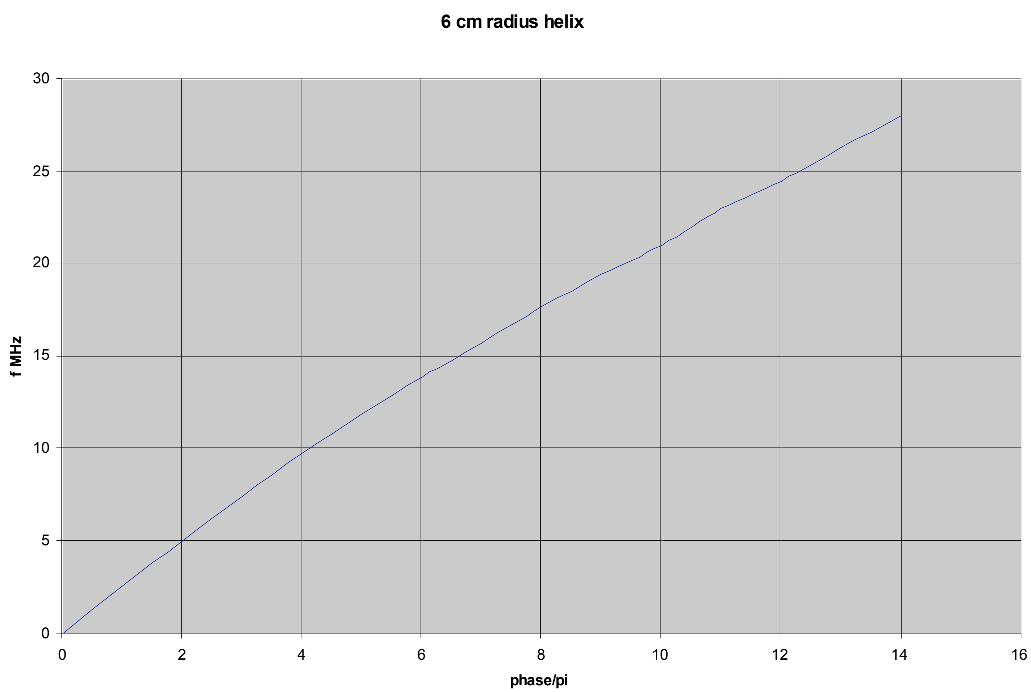
The first model constructed is shown in the picture below. The 6 cm radius, 0.9 meter long helix is wound using copper wire with a diameter of 0.1" and a spacing of 0.1" between the wires (wire to wire period of 0.2"). The helix is mounted on a plastic cylinder centered inside a 10 cm radius metal cylinder, with air as the dielectric media. It was terminated in a resistor that was varied to get what looked like the best match, which was about 1.5 K ohm vs a calculated characteristic impedance of about 1.9 K ohm.



The propagation of a pulsed voltage ramp through the 0.9 meter long helix is shown in the figure below. The delay time from input to output is as expected with a propagation velocity ~ 4.6x10(6) m/sec.



To more accurately quantify the dispersion properties of the helix, measurements were made in the frequency domain with a network analyzer of the phase difference between the output voltage and input voltage vs frequency.



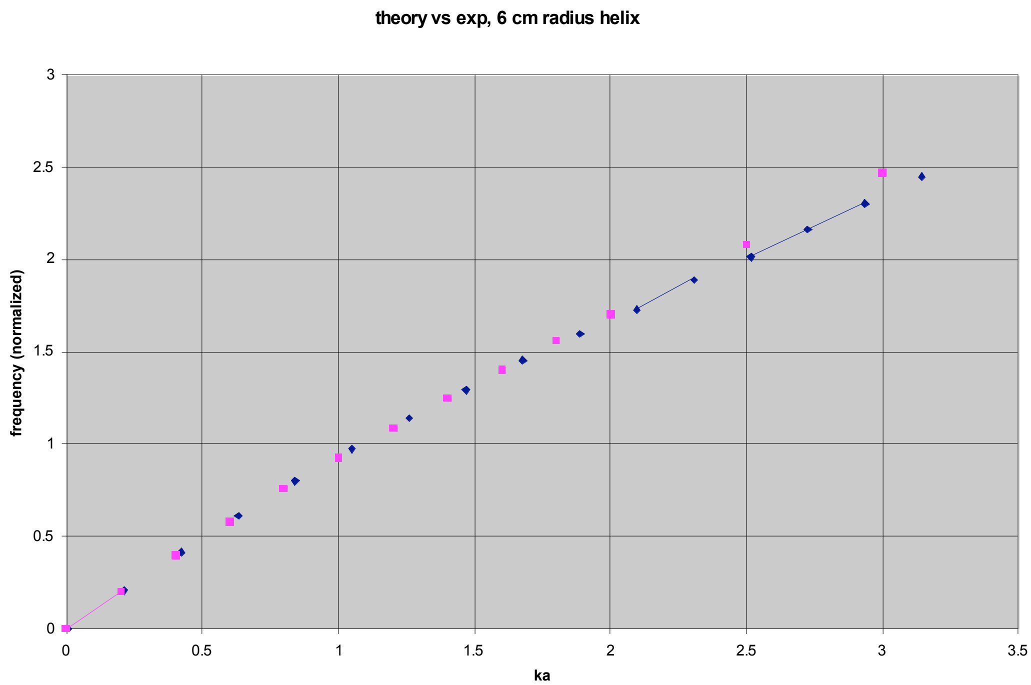
To compare with a sheath helix model, we normalize the frequency as $\omega a / v_0$, where from the measurements of the slope at low frequency the low frequency phase velocity is

$$v_0 = 4.6x10^6 \quad m/\sec$$

We then plot this frequency vs ka, where

$$ka = (\frac{phi}{\square})(\frac{\square a}{helix\ length})$$

The results are shown below, where the data is blue, and the theoretical prediction of the dispersion using a sheath helix model for this configuration is red.



On the modeling front, Scott Nelson is using a 3D Finite-Difference Time-Domain code package to solve for the electromagnetic fields in a helical line via a “first principles” solution of Maxwell’s equations. Another, by Alex Friedman, is using a circuit model to compute the response to an applied voltage waveform, then tracking marker particles to quantify the output energy spread. The plan is to use these methods in tandem, cross-validate them and validate them versus experimental measurements, then to feed the resulting accelerating fields into WARP for fully self-consistent simulations including space charge effects (the influence of the beam back on the circuit is minimal in these small systems).

Drift-Tube Linac concept

(A presentation was made by Andy Faltens; the subgroup working on this topic consisted of Andy Faltens (chair), Peter Seidl, and Steve Lund)

This concept is among the first that had been considered for the Heavy Ion Fusion application, and has a rich history. Indeed, one of the earliest experiments carried out used three "tanks" of a DTL to generate a 2MV, 1A, Cs^+ beam with line charge densities of 0.5-1 μC/m. Various transverse focusing schemes were considered, and the configuration evolved from solenoid focusing, to aperture focusing, to aperture focusing with grids to short the defocusing fields at the gap exits, to a similar concept with shaped grids, to electrostatic quadrupole focusing, to multiple-beam electrostatic quadrupole focusing. It is noteworthy that, when grids were employed, copious electrons added to the focusing significantly. This experiment is depicted in Fig. A.

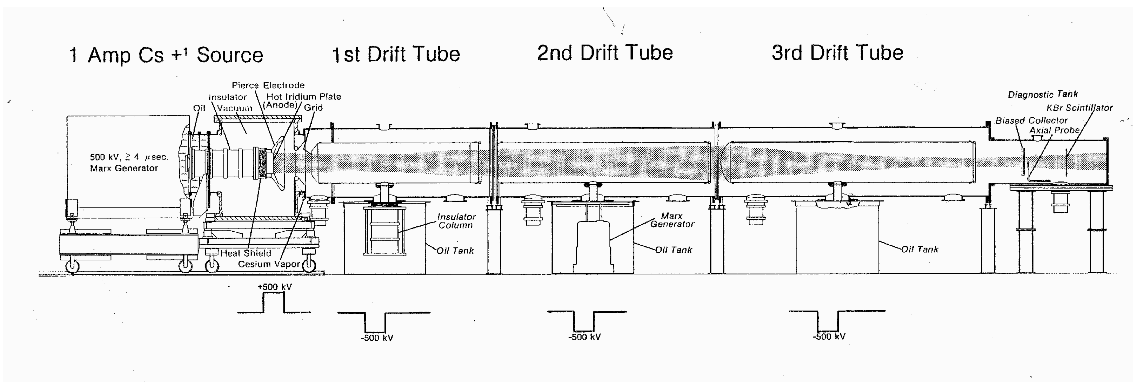


Fig. A. Layout of original drift-tube linac based experiment at LBNL.

The "baseline" HIF concept employs a long initial pulse of ten microseconds or more to obtain the requisite number of ions for target implosion, implying that such a DTL-based fusion system would use long electrodes and so offer a low accelerating gradient; indeed, that consideration led the program toward DC injector architectures such as the Electrostatic Quadrupole (ESQ) injector now used on HCX. For the HEDP accelerator application, which requires only a short pulse, the concept may be especially attractive, with shorter tanks and a larger gradient.

A number of variations are possible, ranging from a system with multiple compact beams launched by multi-beamlet injectors, to one with much larger sources. Since the voltage pulses do not require that ferromagnetic cores surround the beams, the system cost is expected to be quite insensitive to the transverse cross-sectional area of the beam transport system, in marked contrast to a multi-beam induction linac.

One variation of an HEDP accelerator uses multiple beams inside each drift tube, injected initially from compact sources at 750 keV and transversely confined by electrostatic quadrupoles. See Fig. B. This system uses transport lines similar to those of HCX: $L_{half\text{-}period} \sim 50$ cm; $L_{electrodes} \sim 30$ cm; $\lambda \sim 1/4$ μC/m; beam semi-axes ~1 cm and 1.5 cm; $I_{beam} \sim 1$ A; $J_{source} \sim 100$ mA/cm^2; 100 ns flat-top, 100-200 ns beam head, and 100-200 ns beam tail; drift tube switching time 100-200 ns; drift tubes 1-2 m long.

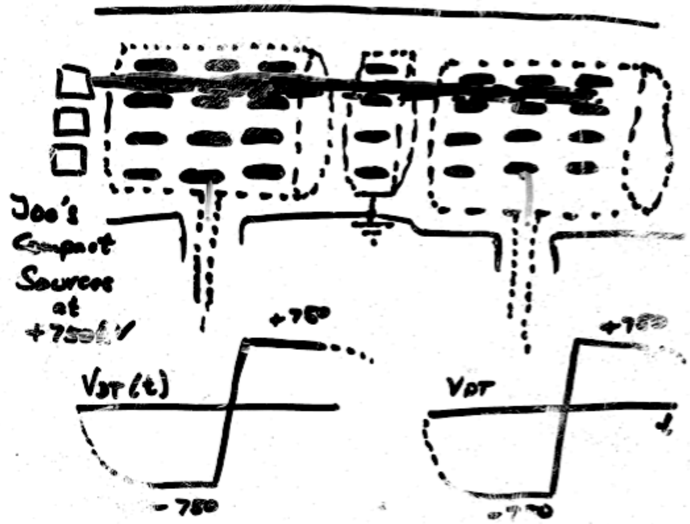
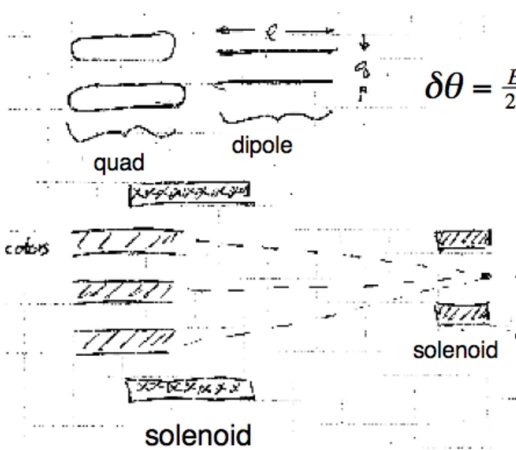


Fig. B. Multi-beam DTL configuration

For final compression, a velocity "tilt" is imparted by the final drift tube. For a constant bunch length scenario, T_p has decreased as $1/E^{1/2}$. Also, $T_p \approx 30$ ns, *e.g.* $\Delta V/V \approx$ (1 MeV)/(10 MeV), $\Delta v/v \approx 1/20$, and a longitudinal focus in 20 bunch lengths, or 6 meters. The large tilt would imply a significant chromatic variation of the focal spot with time. This can be avoided by deflecting the beam using time-dependent dipole fields imparted by a pulsed high-voltage deflector; it could be tapped off of the same pulser that imparts the tilt. See Fig. C.



$$\delta\theta = \frac{El}{2T} = \left(\frac{l}{2g}\right)\left(\frac{V}{T}\right) \approx \frac{(10)(100kV)}{(2)(10MV)} = 50mr$$

Fig. C. Focusing for DTL example.

The group also discussed briefly a related concept, the resistively-graded column. In such a system, and in contrast with a DTL, the beam spends very little time "coasting." The ESQ injector is of this nature, as might be the column in a load-and-fire system.

High-Gradient Induction Accelerator concept

(A presentation was made by George Caporaso)

In this concept, a planar stack of blumleins inside a ferromagnetic core functions as a voltage adder. The concept takes advantage of newly available technologies: strip-line materials with dielectric constants up to 45 and high-gradient insulators. The goal is an accelerating gradient of 3-5 MV/m. At present, it appears that the accelerating waveform will be set by the geometry (it is not tunable), and the existing concept is limited to pulses of 20-40 ns duration; the latter may be stretched somewhat by the use of spiral lines. The fast switches needed for this concept are still in development.

Multi-Pulse Induction Linac concept

(A presentation was made by Grant Logan)

Replace long injected bunch with many short pulses into load and fire section, drive induction cores with smaller volt-seconds repetitively with fast-reset pulse-forming networks (PFNs). Tailor □(z) and waveforms for continuous acceleration and compression to desired pulse train with velocity tilts into neutralized drift region for longitudinal merging. See Fig. X.

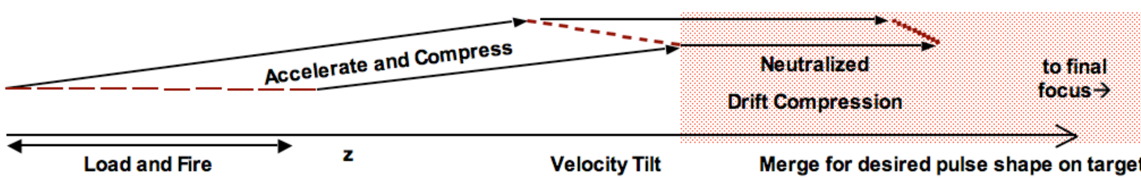


Fig. X. Multi-pulse induction accelerator with a sequence of high line charge density beam pulses, using solenoid focusing

Constraints: For any linac, minimum length for last pulse to catch up to first pulse. Longitudinal invariant limits input pulse train length for acceptable momentum spread on target. Achromatic focusing (Lee) or assisted pinches (Yu) accept higher momentum spreads→ longer input pulse trains allowed.
Potential Benefits: For any linac, multi-pulsing reduces upstream □, perveance. Allows more pulse shaping and data sampling on target per shot. *For induction linacs, multi-pulsing increases acceleration gradients (due to shorter pulses). Lower core mass (volt-seconds) savings offset higher pfn network costs.*
Preliminary conclusions from the multi-pulse study were:

- Multi-pulsing up to 5-20 pulses appears feasible under “conventional” (but still-to-be-determined) longitudinal momentum spread limits, and induction gradient limits.
- For reasonable maximum core radial builds (V-s/m limits) minimum induction linac lengths for tail pulse to catch up to the head pulse will likely be ~ 2-3 x longer than for single pulse cases for short pulse HEDP cases, *but comparable for longer pulse IFE cases*.
- Multi-pulsing can lower total linac core volt-seconds and peak line charge densities by a factor roughly ~ $Np^{1/2}$, for the same total delivered beam energy.

- Fast-reset pfn network costs need to be evaluated. If future fast switching costs go down, multi-pulsing is likely to reduce total costs, while enhancing target pulse shape capability.
- Gas and electron cloud effects for multi-pulses need to be evaluated. (Total beam charge ~ same, load-in times longer, peak line-charge densities lower with multi-pulses compared to single pulse)

Physics Constraints

(Presentations were made by Roger Bangerter and Steve Lund)

For all these concepts, both the transverse and longitudinal phase-space “budgets” must be carefully monitored. For one HIF driver case using neutralized drift compression, LSP simulations to date show a 20 MeV energy spread acceptance in compression and focusing; thus, with a 5 ns pulse length, the longitudinal admittance is of order 0.1 eV-s. The source temperature of order 1 eV, when boosted and multiplied by the 20 microsec initial pulse duration, gives an emittance of order 0.1 eV-s, so that this case is on the edge of feasibility. A similar estimate for the BBTWA HEDP case described above shows that the parameters are within the acceptable range based on this one consideration, but without a large safety factor. Waveform errors of ~1% can be significant.

In addition, beam mismatch must be kept to acceptable limits; this constrains the rapidity with which energy “tilt” can be applied, and other transitions effected. Recent work has clarified these constraints.

List of Participants in Working Group 3

(Not all were present at the same time)

Dick Briggs (co-chair)

Alex Friedman (co-chair)

Roger Bangerter

Santiago Bernal

Frank Bieniosek

Ned Birdsall

George Caporaso

Christine Celata

Yu-Jiuan Chen

Shmuel Eylon

Andy Faltens

Enrique Henestroza

Bill Herrmannsfeldt

Igor Kaganovich

Joe Kwan

Grant Logan

Steve Lund

Scott Nelson

Craig Olson

Lou Reginato

Tim Renk

Prabir Roy

Peter Seidl

Will Waldron