Studies of the Pulse Line Ion Accelerator (PLIA)

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Outline

- Motivation
- Concept and design considerations
- Initial testing with beam
- HV testing
- PLIA for NDCX-II
- Conclusion

The motivation for the Pulse Line Ion Accelerator concept came from ion beam requirements for High Energy Density Physics

From the Workshop on Accelerator Driven High Energy Density Physics in October 2004 at LBNL:

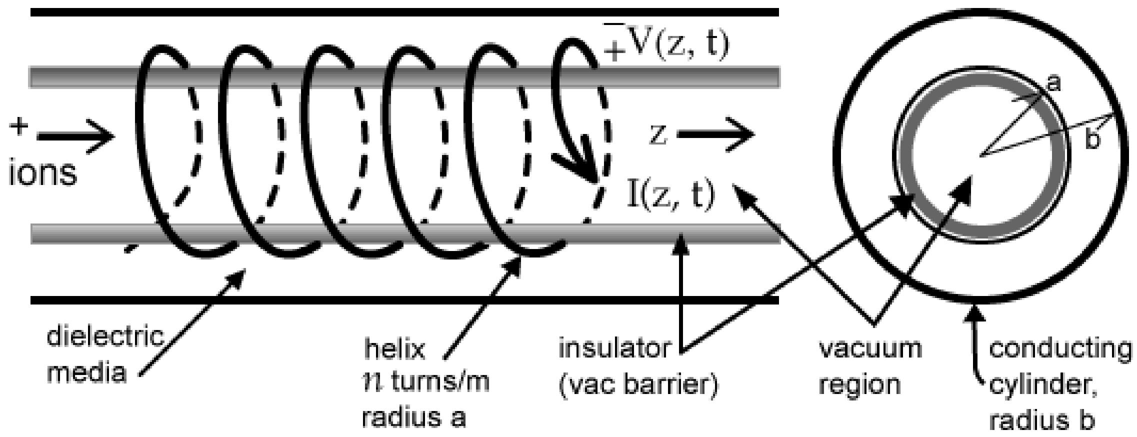
- Volumetric heating at Bragg peak yields < 5% target temperature variation with 75% of the ion energy deposited in target
- Beam on target: ~0.1 microcolumbs of medium mass ions at an energy slightly above the Bragg peak in as short a pulse as possible (~1 ns) with ~1 mm spot size

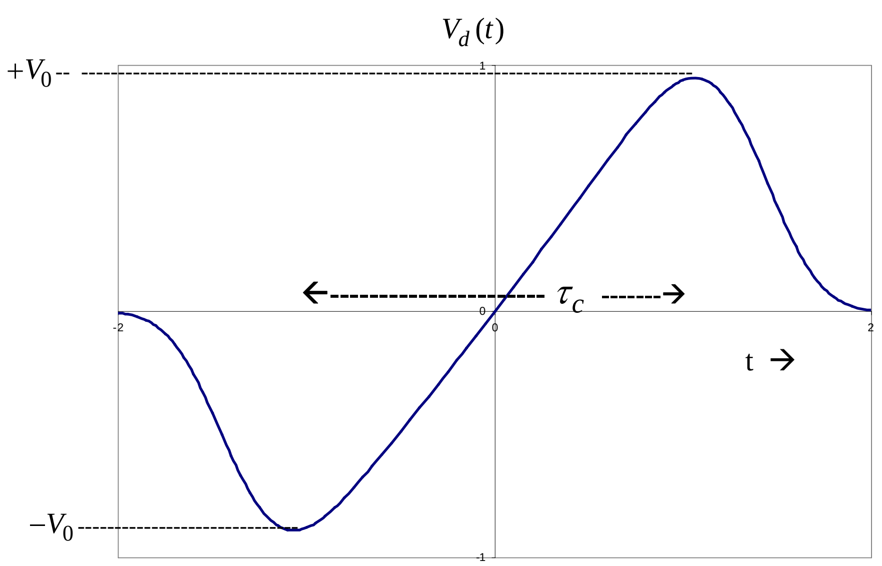
The Pulse Line Ion Accelerator (PLIA) combined with neutralized drift compression appears to be an inexpensive solution to meet these requirements.

The majority of the cost for the PLIA concept is the large bore 5-10T superconducting solenoid

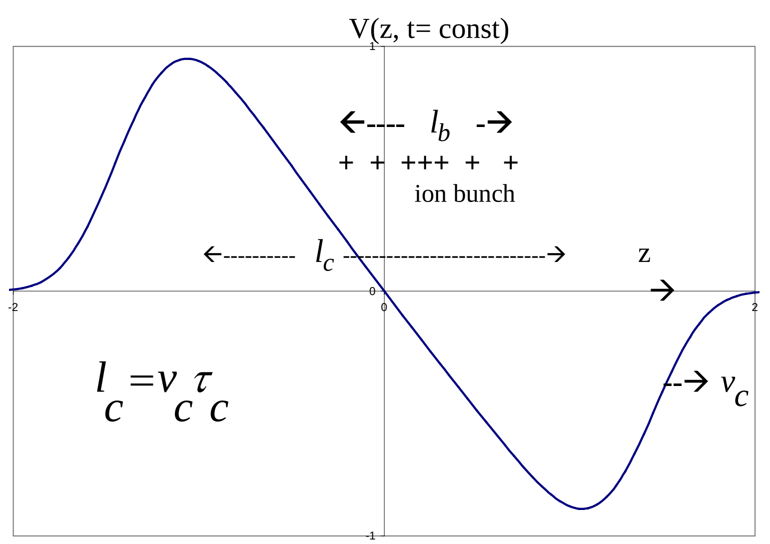
Commercially available solenoids meet the requirements (e.g. ICR mass spectroscopy solenoids from Oxford Instruments).

PLIA concept: A pulsed power driven traveling wave on a helical pulse line accelerates the ion bunch





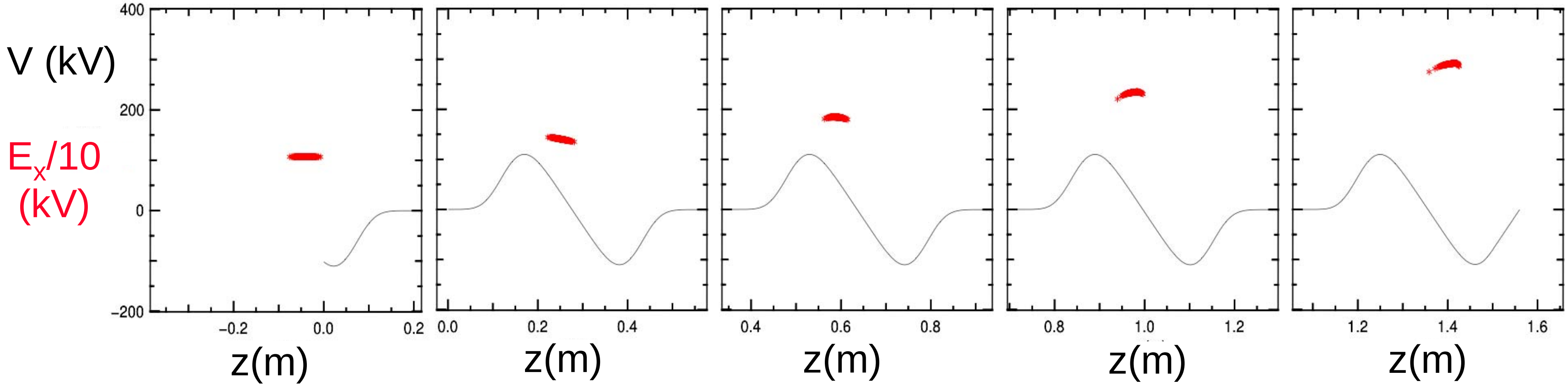
drive voltage $V_d(t)$ applied to helix input



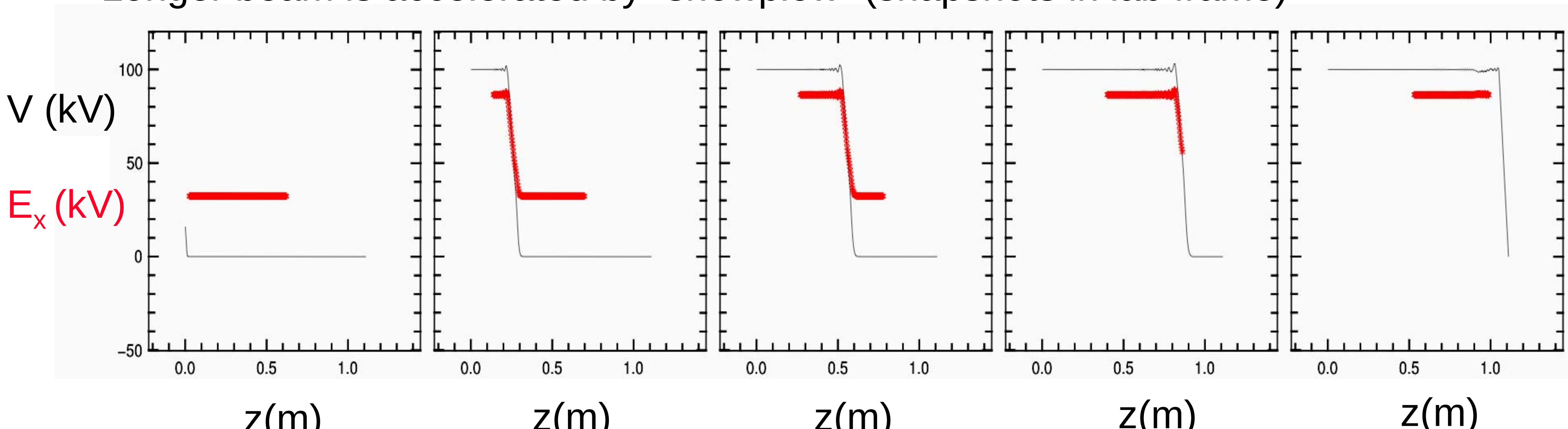
snapshot of the voltage propagating V(z, t=constant)

PLIA can be operated in a short-pulse “surfing” mode or a longer-pulse “snowplow” mode

Short beam “surfs” on traveling voltage pulse (snapshots in wave frame)



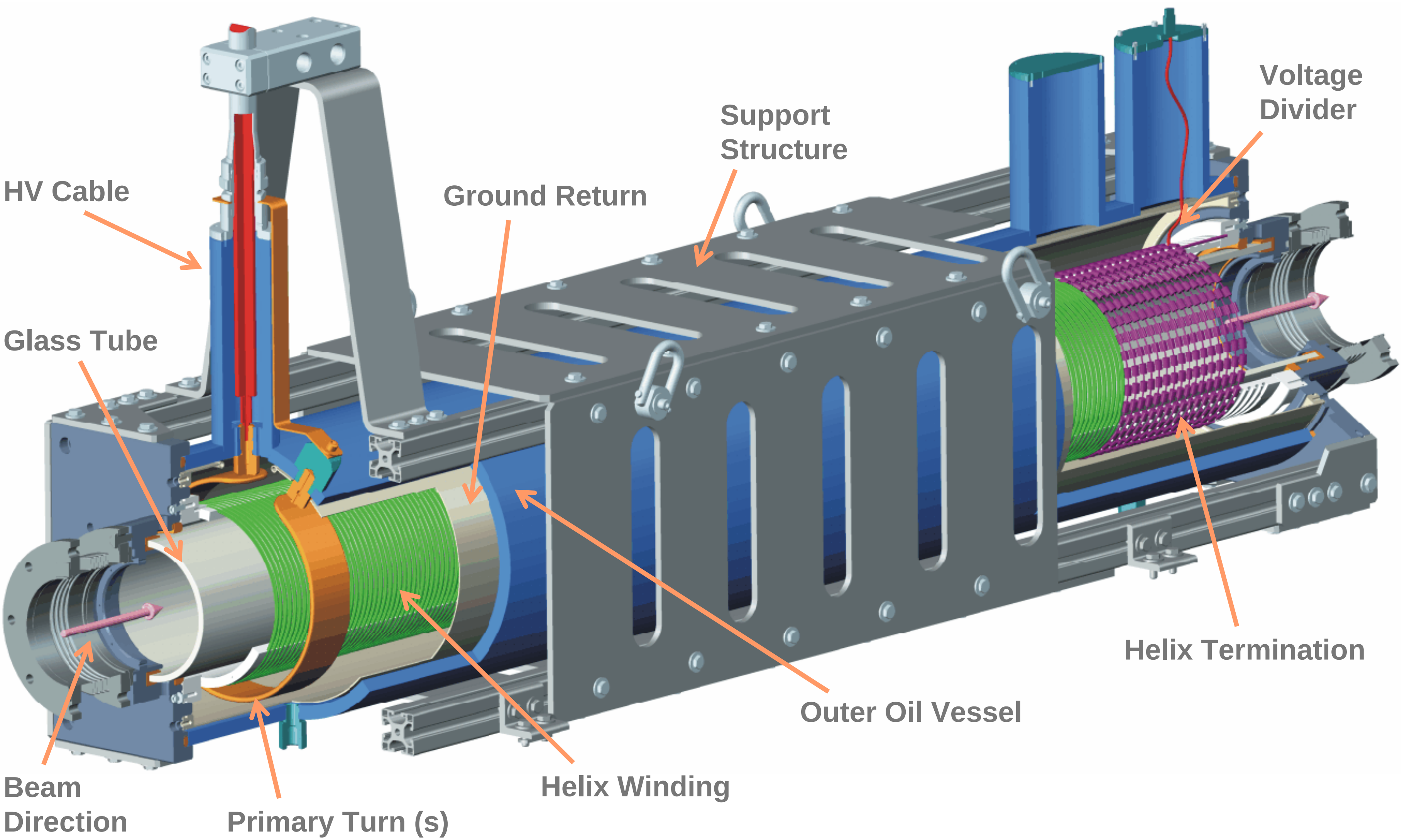
Longer beam is accelerated by “snowplow” (snapshots in lab frame)



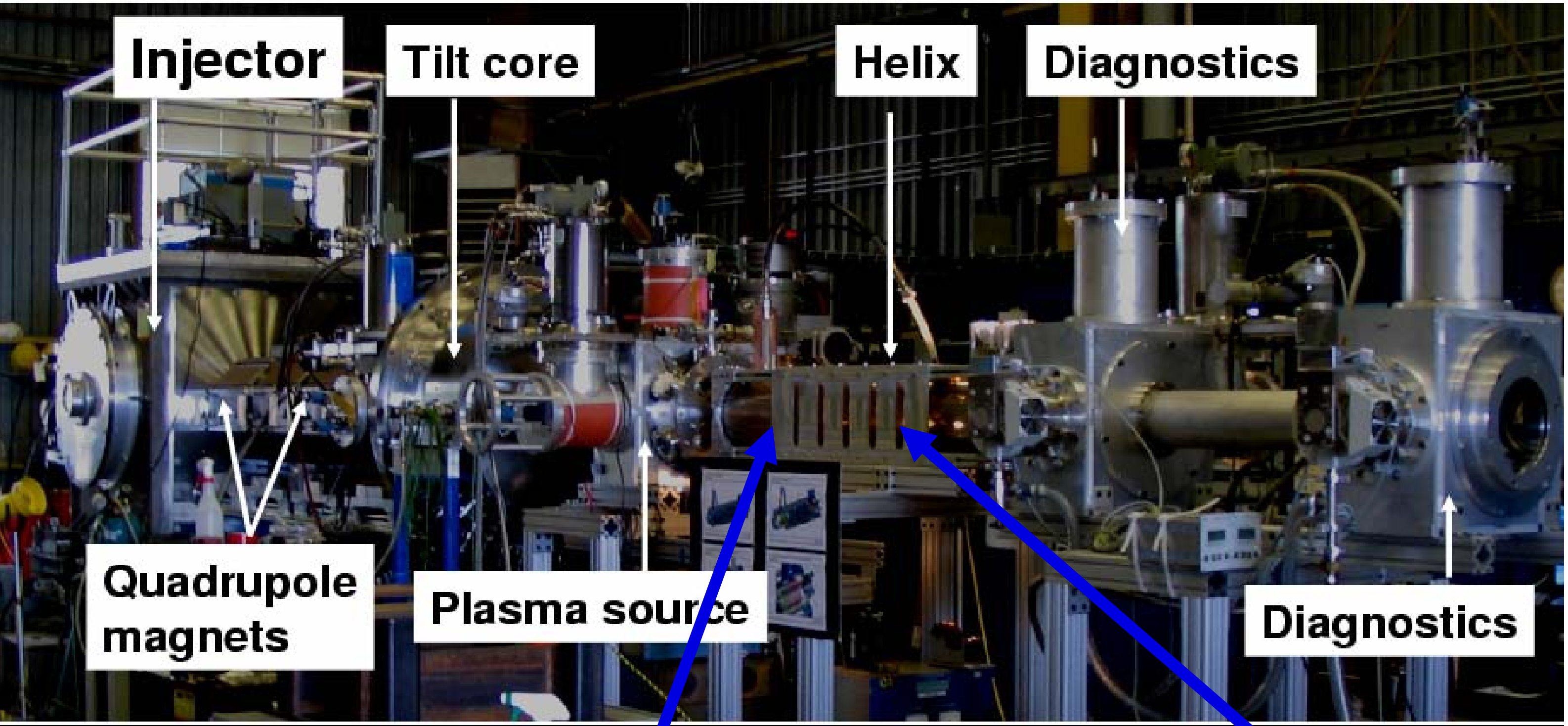
PLIA Design Constraints

- Bandwidth of the propagating pulse and the dispersion properties of the line (distortion)…The Fourier spectrum of pulse should be contained in ka < 1 which limits the ramp length to a minimum of $\sim\pi a$ and hence limits the acceleration gradient.
- Radial decay of “short wavelength components” of the accelerating E field
- Beam loading leading to attenuation and distortion of the drive pulse
- Amplification of small fluctuations (“TWT instability”)
- Voltage breakdown from radial and axial electric fields in the dielectric
- Voltage breakdown from axial electric fields along the surface of the vacuum insulator (with and without stray particles and gas clouds)

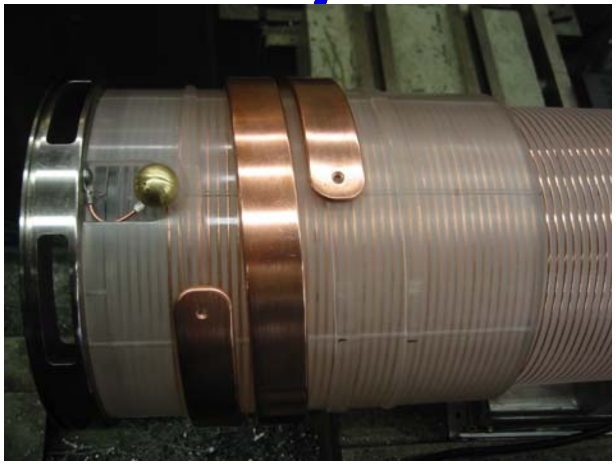
Oil dielectric indirect-drive PLIA for proof-of-principle test with beam



PLIA proof-of-principle experiment on NDCX-I

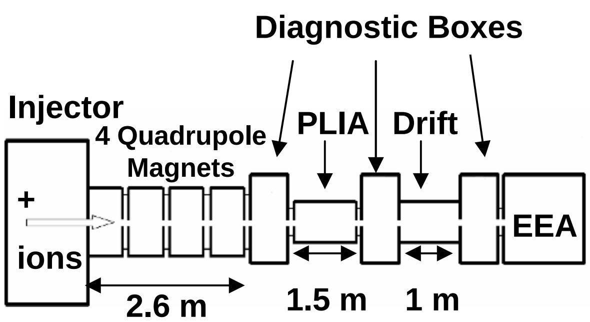


transformer coupling with 2-turn primary (step-up)

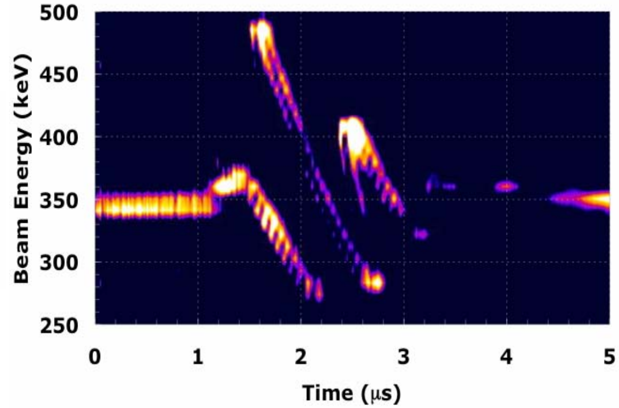


helix with matched resistive termination

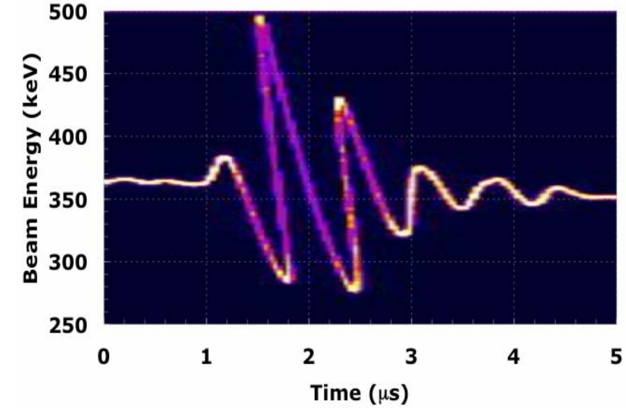
Proof-of-principle PLIA test with a 1 mA, 350 keV K+ beam displayed acceleration, deceleration, and longitudinal bunching



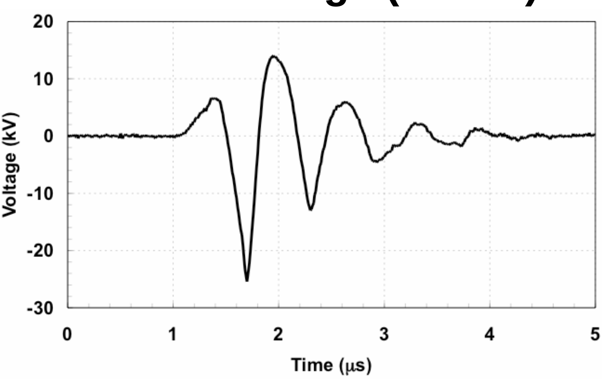
Experiment



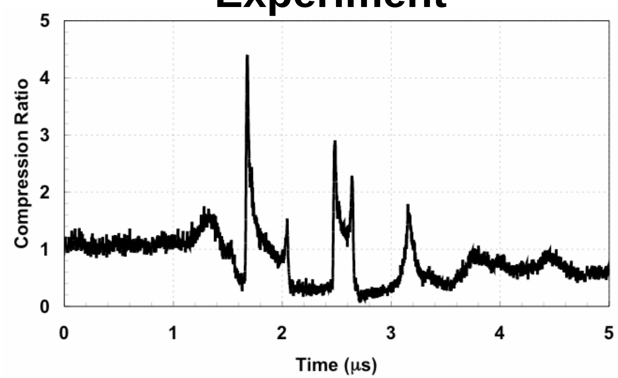
WARP Calculation



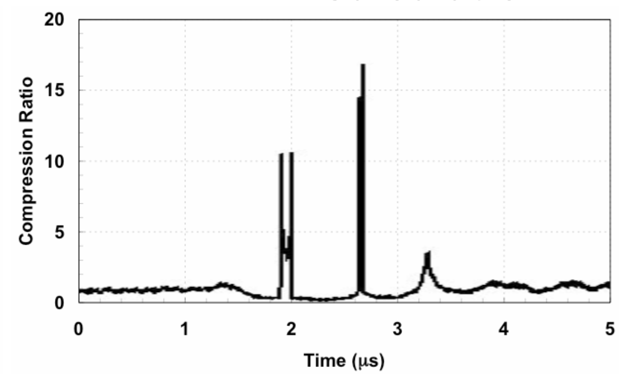
PLIA Voltage (at end)



Experiment



WARP Calculation



The voltage gradient was limited to < 2 kV/cm by partial discharges in the vacuum. Pressure bursts and visible light were still observed during this testing, but the voltage waveform was minimally loaded and reproducible.

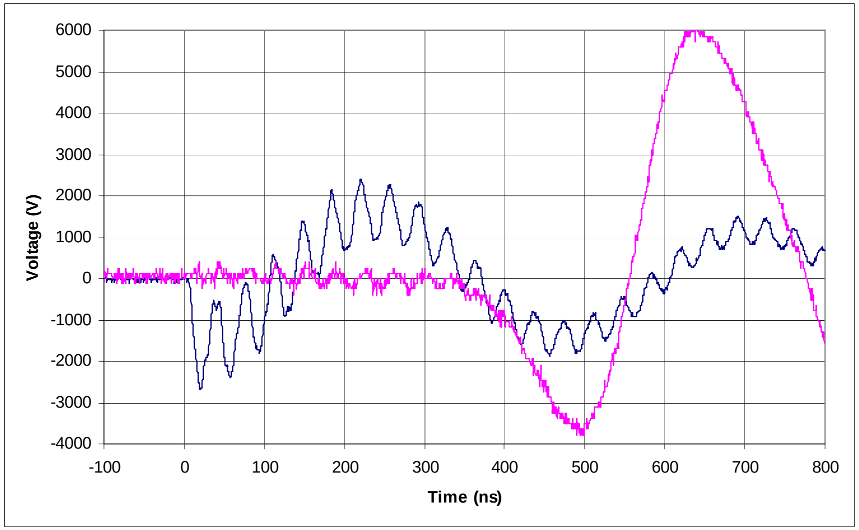
After the proof-of-principle experiment was completed, HV tests started to explore the cause of the partial discharges

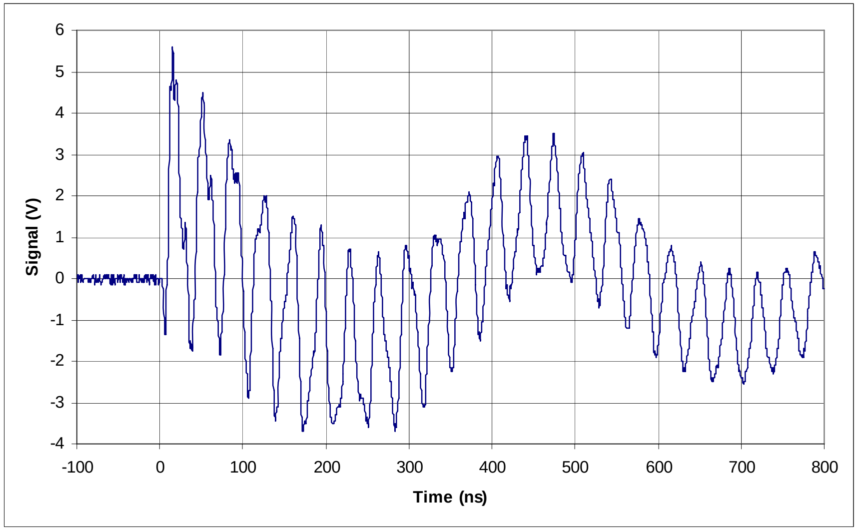
- **23 kV/cm was achieved with an undamped ringing voltage waveform (2-3 MHz) applied to a coil around a glass tube. No visible light or pressure bursts were observed. The test was limited to these levels by the voltage capability of the pulser.**

- **Previously, the only diagnostic which was available was the resistive voltage divider which was part of the termination resistor string. For this round of tests, capacitive pickups were placed along the helix structure to monitor the traveling wave and a current transformer was placed around the output of the high voltage pulser. Some experiments were also done with a high voltage probe looking directly at the input to the helix primary and a B-dot loop inside the glass tube.**

- **To investigate the effect of attenuating the magnetic field at the vacuum surface of the insulator from the helix current, many closed rings were placed at the OD of the glass insulator. This modification did not improve the high voltage performance, but did lower the characteristic impedance and increase the wave speed from 1.9 m/us to 2.6 m/us.**

Initial HV tests without beam showed 28 MHz ringing on the helix primary and the helix





Blue trace is the primary voltage

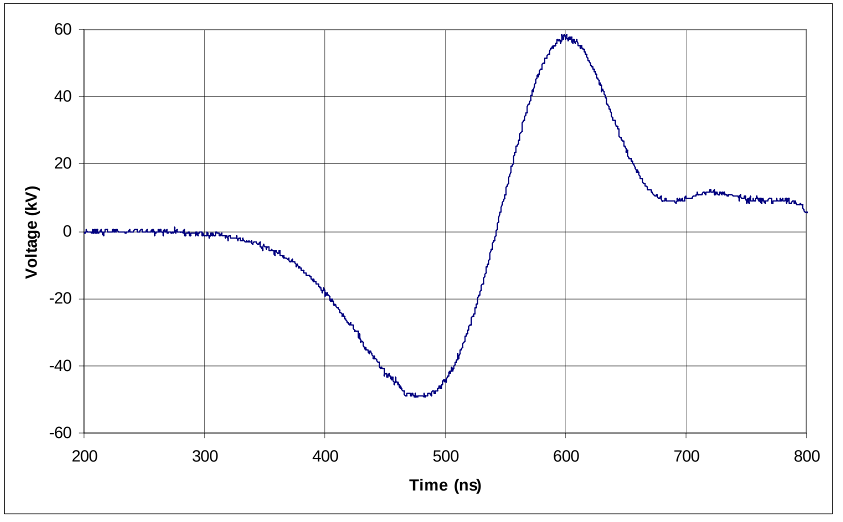
Pink trace is the helix termination voltage

B-dot loop looking at Bz at the glass ID surface within the primary section of the helix

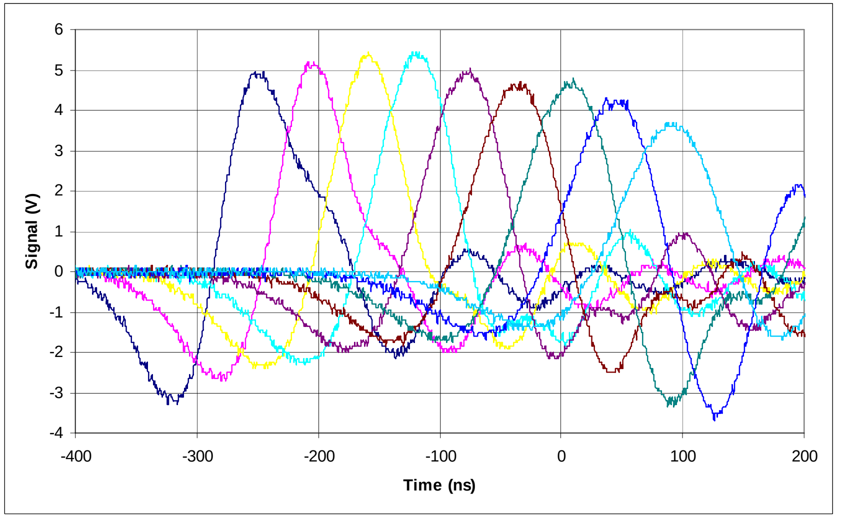
High frequency ringing was likely the cause of the partial discharges during the proof-of-principle experiment

- This ringing could not been seen on the output termination resistive divider because of dispersion along the line at this frequency.
- The capacitive pickups showed the amplitude of these oscillations decreasing quickly as the wave travels down the transmission line.
- The amplitude of this oscillation on the B-dot was significantly less at the center of the glass tube because fields at these high frequencies do not leak very far past the helix windings.
- It is almost certain that the helix and pulser used for proof-of-principle test with beam produced this same ringing, but the diagnostics were inadequate to observe the effect.

Waveforms after significant modifications to the pulser to reduce the 28 MHz ringing (shorter cable, filter network, damping resistor)



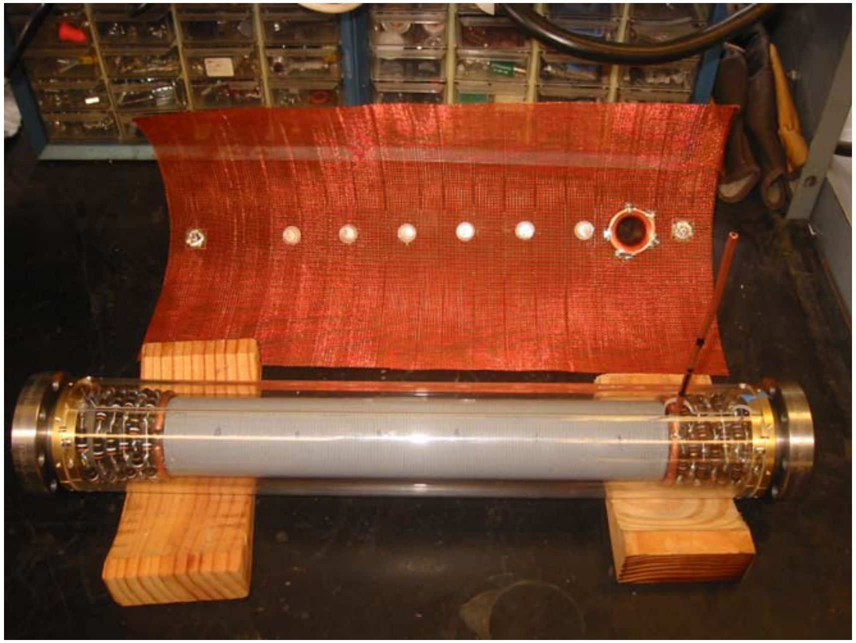
Helix termination voltage without partial discharge

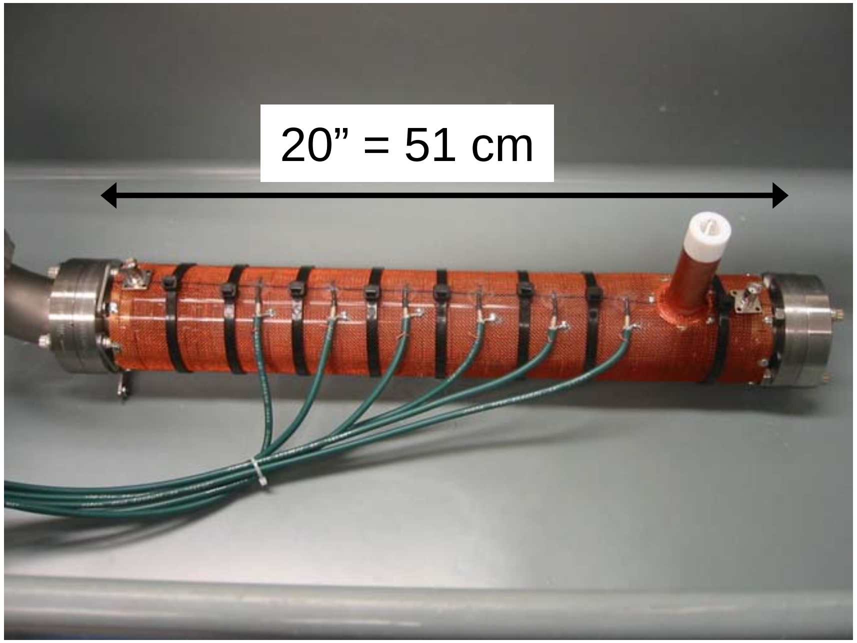


Signals from the capacitive pickups located every 10 cm along the PLIA without partial discharge (capacitive pickup signal is proportional to the time derivative of the voltage)

Peak voltage gradient of ~7 kV/cm and an average voltage gradient of ~6 kV/cm with partial discharges occurring < 10% of the time and minimal loading on the traveling wave (pulser limited the achievable gradient)

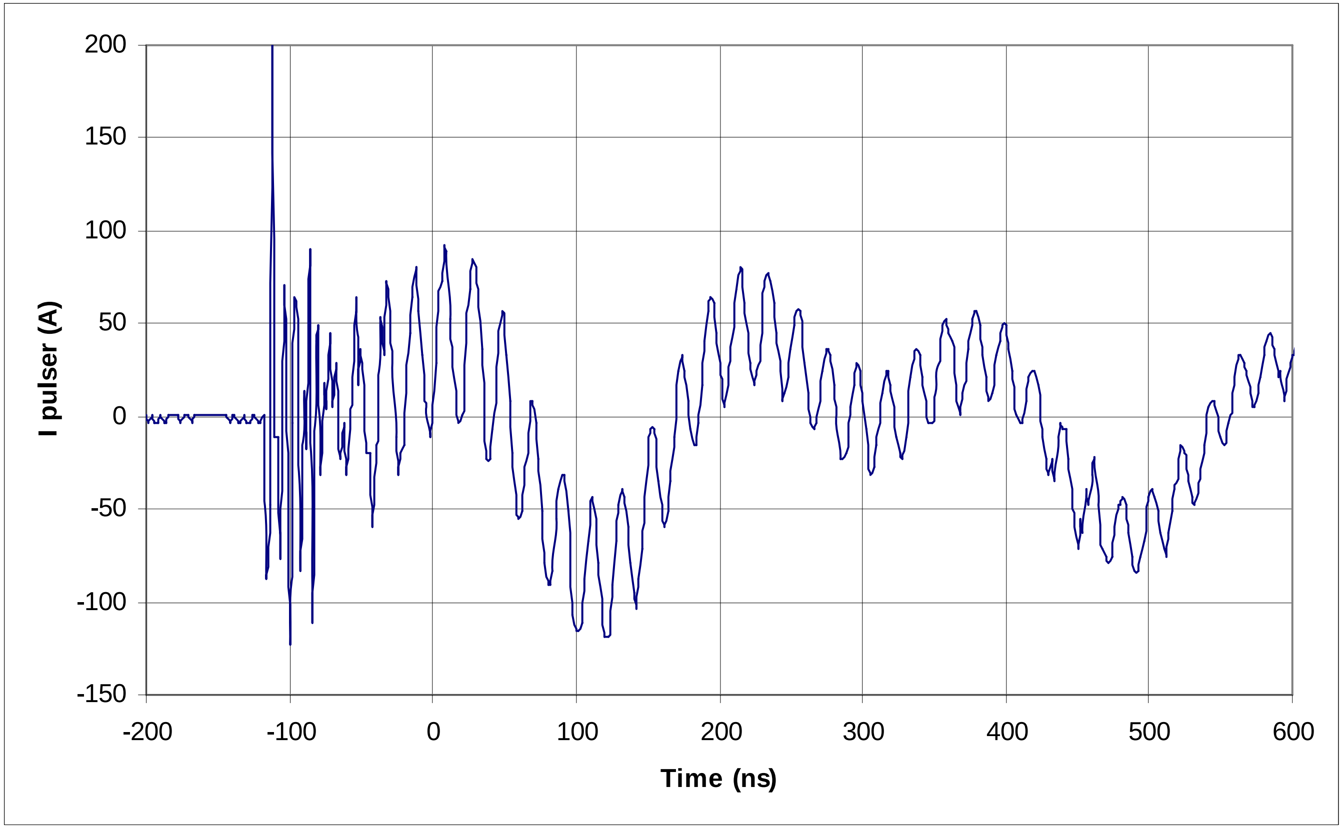
Scaled helix for high gradient testing at lower peak voltages (without beam)





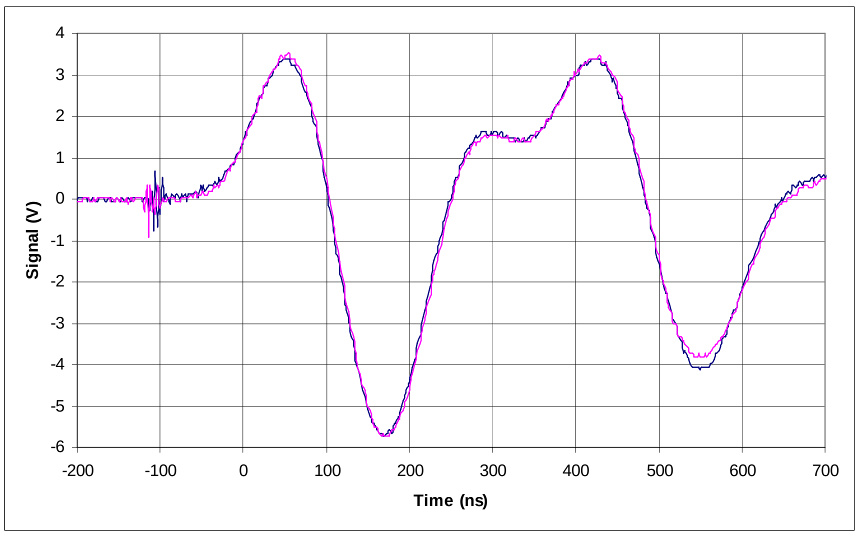
- **Small dimensions so that the structure can support shorter ramp lengths (~8 cm)…less voltage needed to get to high gradients**
- **Small dimensions to fit inside existing 3T pulsed solenoids**
- **Direct drive for a simpler field geometry at the input to the helix**
- **Resistive divider to grade and measure the input voltage**
- **Resistive divider to grade, terminate, and measure the output voltage**
- **Capacitive pickups along the helix (6)**

Initial scaled helix testing showed 50 MHz ringing on the pulser output current and partial discharges occurring > 50% of the time

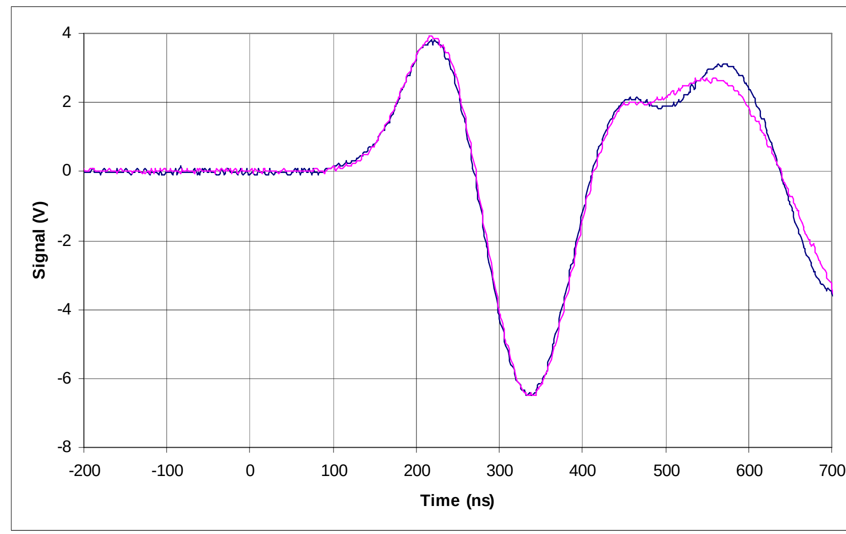


Scaled Helix voltage waveforms showing a peak gradient at the input of ~3.5 kV/cm with minimal loading when partial discharges occur and no 50 MHz

Input voltage (raw signal)



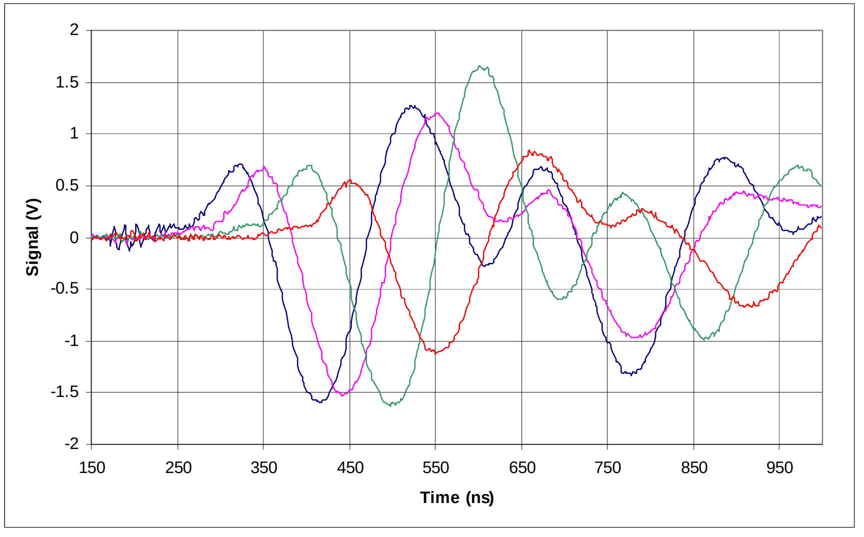
Output voltage (raw signal)



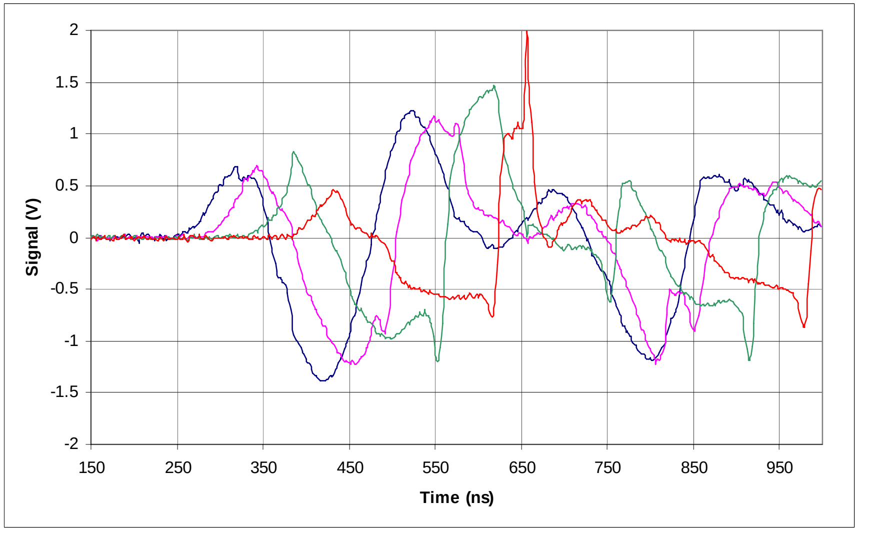
Blue traces are without a partial discharge.
Pink traces are with a partial discharge.

Scaled Helix Capacitive Pickups (proportional to the time derivative of the voltage)

Out of 6 pickups which are 5 cm apart, these waveforms are for 1, 2, 4, and 6. Pickup 1 is closest to the helix input and pickup 6 is closest to the helix termination.



No observed partial discharge



With partial discharge

With vacuum, these glitches in the signals occur at the same time and propagate at the nominal wave speed. Other diagnostic waveforms are not distorted, implying either differences in bandwidth or modes other than the “helix mode” between the helix and the return shield. These glitches do NOT occur with air in the glass tube.

Initial scaled helix conclusions

- **The partial discharges are not exclusive to a particular input coupling field geometry (direct or indirect).**
- **The glitches seen on the capacitive probes are the result and not the cause of the partial discharges.**
- **The 50 MHz on the pulser current needs to be understood and eliminated (damping impedance, bandpass filter, reducing strays, impedance matching).**
- **Further tests will attempt to better characterize the structure as a load at different frequencies.**

Possible application of the PLIA

- The Neutralized Drift Compression Experiment (NDCX-I) at LBNL has successfully demonstrated the ability to radially and longitudinally compress space-charge dominated K+ beams to ns pulse widths and mm spot size.

- NDCX-I uses a solenoid transport system, a bunching induction module, and a volumetric plasma source to neutralize the beam and overcome space-charge forces.

- The purpose of the NDCX-II is to use the same technique for HEDP and WDM studies which require more energy deposited on the target.

Possible application of the PLIA

- To make NDCX-II more affordable, the induction cells and Blumleins from the Advanced Test Accelerator (ATA) at LLNL are available which were designed for 70 ns pulses.

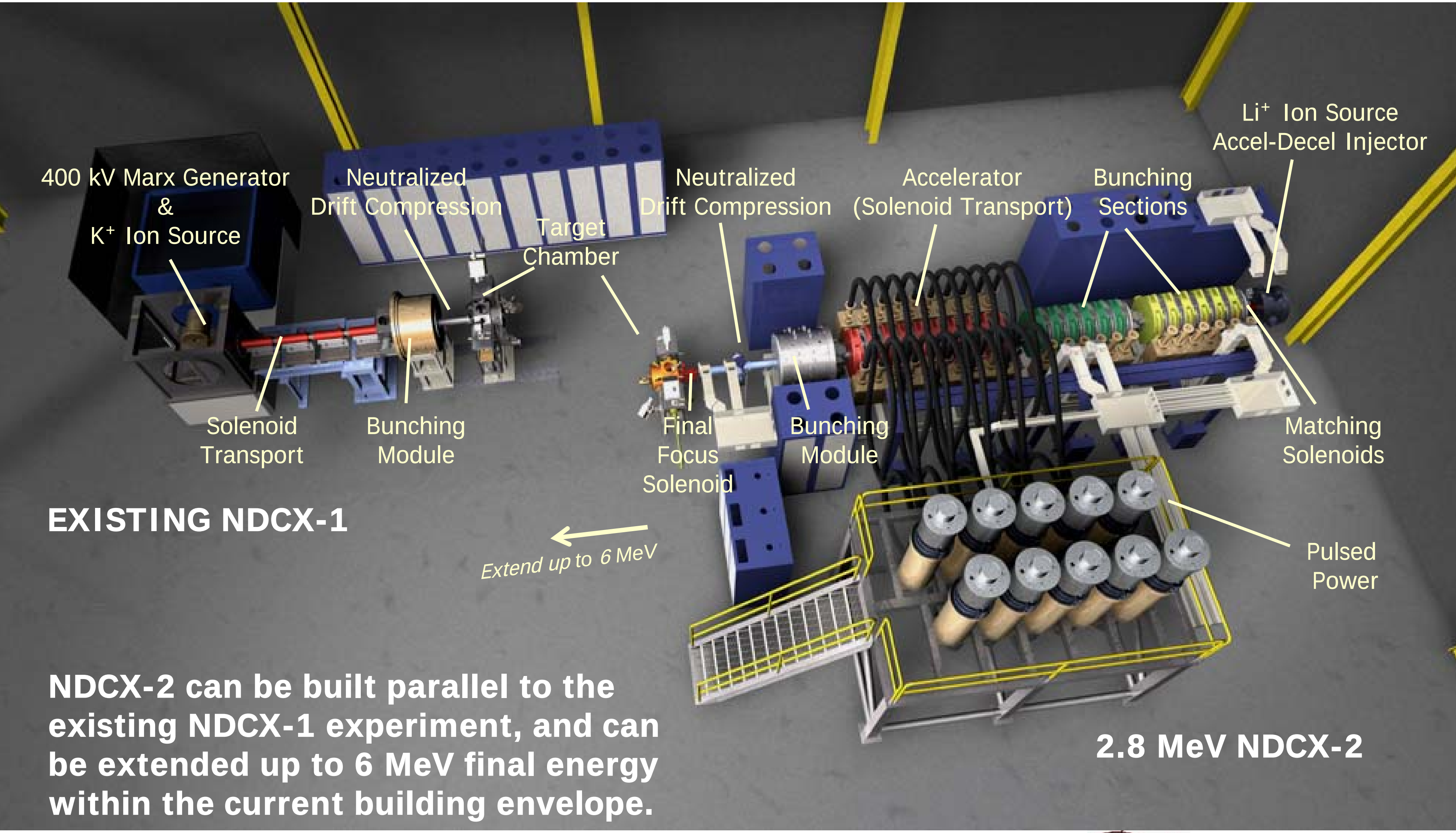
- To get the charge we need from known ion sources, the beam pulse width has to start at several hundred ns.

- This longitudinal compression to match into the ATA cells can be achieved with multiple induction cells or a single untapered PLIA operating in the snowplow mode.

- The multiple induction cell approach requires various ramped voltage waveforms on long time scales. New pulsers would need to be designed and fabricated.

- The PLIA approach is attractive because the slow-wave structure is simple to fabricate and only one high voltage pulser is required, but the large superconducting solenoid does introduce some cost.

NDCX-I and NDCX-II at LBNL



NDCX-2 can be built parallel to the existing NDCX-1 experiment, and can be extended up to 6 MeV final energy within the current building envelope.

Conclusion

- **Both direct and indirect drive helical pulse lines have been fabricated and tested.**
- **Useful electric field gradients have been achieved, but partial discharges in the vacuum still occur intermittently.**
- **High frequency ringing from the spark gap based drive pulser is the most likely cause of these partial discharges and means for further reduction of this ringing are being explored.**
- **Variations in applied axial magnetic field, voltage waveforms, and grading ring configuration will also be used to attempt to suppress these partial discharges.**
- **Because we have demonstrated beam bunching and acceleration, and have attained useful gradients, studies will continue to look at applications of the PLIA for bunching and acceleration in NDCX-II.**

Related Talks and Posters

PLIA simulation posters

WEPMS016: **A. Friedman, *et al.*, "Modeling the Pulse Line Ion Acelerator (PLIA); An Algorithm for Quasi-static Field Solution"**

WEPMN117: **E. Henestroza, *et al.*, "Electromagnetic Simulations of LBNL Pulse Line Ion Accelerator (PLIA) Experiments"**

Talks on using heavy ions for warm dense matter experiments

MOOBC02: **F. Bieniosek, *et al.*, "Experiments in Warm Dense Matter using an Ion Beam Driver"**

WEOCC02: **P. Ni, *et al.*, "Overview of warm-dense-matter experiments with intense heavy ion beams at GSI-Darmstadt"**

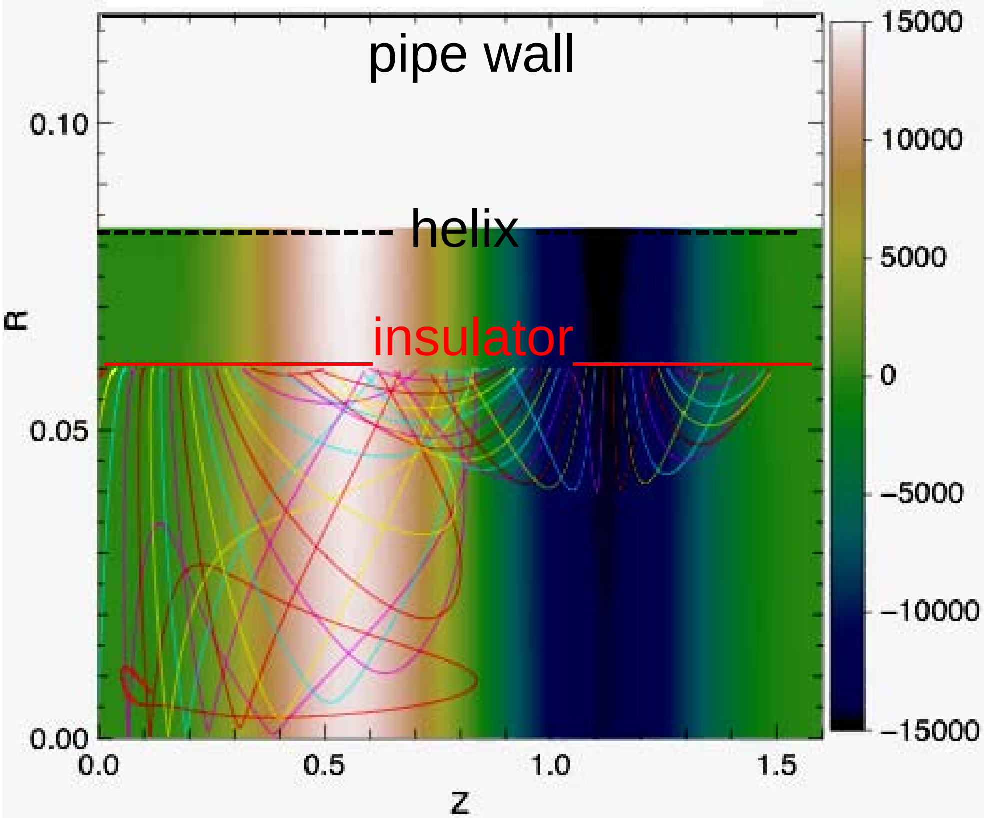
WEZC02: **A. Sefkow, *et al.*, "Extreme Compression of Heavy Ion Beam Pulses: Experiments and Modeling"**

EXTRA SLIDES

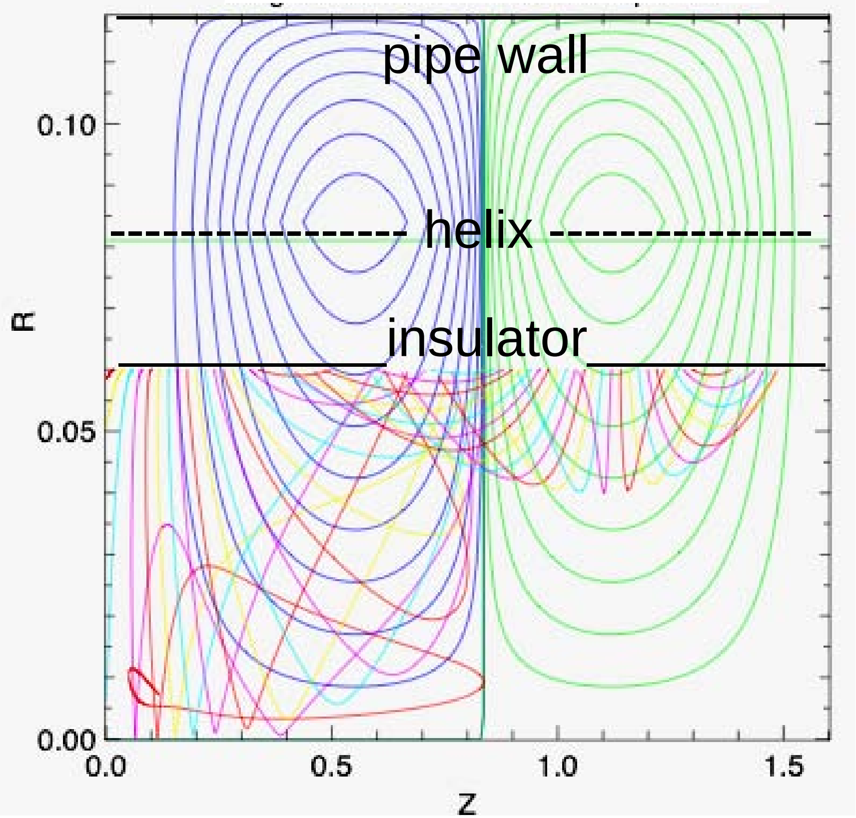
To understand the partial discharges, we are using WARP to follow "tracer" electrons emitted from the insulator surface

Time = 135 ns

Tracers overlaid on contours of the electrostatic potential



Tracers overlaid on B field lines



- Tracers are emitted with zero velocity in the lab frame
- Helix fields are "frozen" in the wave frame (assumes dispersionless wave)
- These images are in the wave frame

An oil dielectric helix with epoxy insulator has been built but not tested. This helix provides voltage grading at the epoxy vacuum insulator surface.