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NDCX-II Beam Dynamics*

A. Friedman, J. J. Barnard, R. H. Cohen, M. Dorf, D. P. Grote, S. M. Lund, W. M. Sharp, *LLNL*

A. Faltens, E. Henestroza, J. W. Kwan, E. P. Lee, B. G. Logan, P. K. Roy, P. A. Seidl, J.-L. Vay, W. L. Waldron, *LBNL*

R. C. Davidson, E. P. Gilson, I. D. Kaganovich, E. A. Startsev, *PPPL*

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Fusion Energy Sciences

The Heavy Ion Fusion Science Virtual National Laboratory

BERKELEY LAB PPPL

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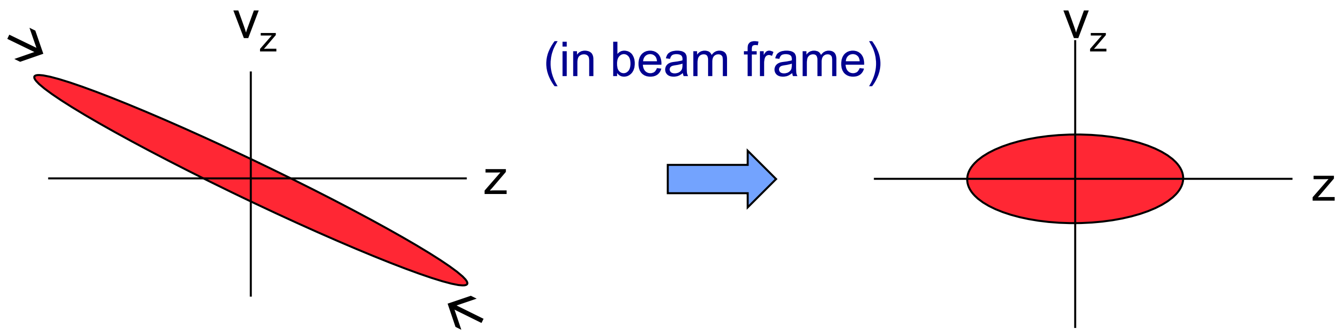
Abstract

The Neutralized Drift Compression Experiment-II (NDCX-II) will produce ion beams for studies of Warm Dense Matter, target physics, and intense-beam dynamics relevant to heavy-ion-driven Inertial Fusion Energy. NDCX-II will accelerate a 20-50 nC Li pulse to 1.2-3 MeV, compress it to sub-ns duration in a neutralizing plasma, and focus it onto a target. We present: the NDCX-II machine layout and "physics design" [A. Friedman, et al., Phys. Plasmas 17, 056704 (2010)], including the use of high-occupancy pulsed-solenoid focusing and modified induction cells from LLNL's Advanced Test Accelerator; unusual aspects of the beam dynamics (such as the use of the beam's space charge to remove the applied head-to-tail energy tilt and halt the initial non-neutral compression in the accelerator); the simulation studies that enabled the design; estimates of robustness; prospects for using dipoles to correct for residual misalignments of the magnetic axis (and thereby suppress detrimental "corkscrew" oscillations of the beam centroid); plans for commissioning over the coming months; and some possible experiments using the machine itself and extensions.

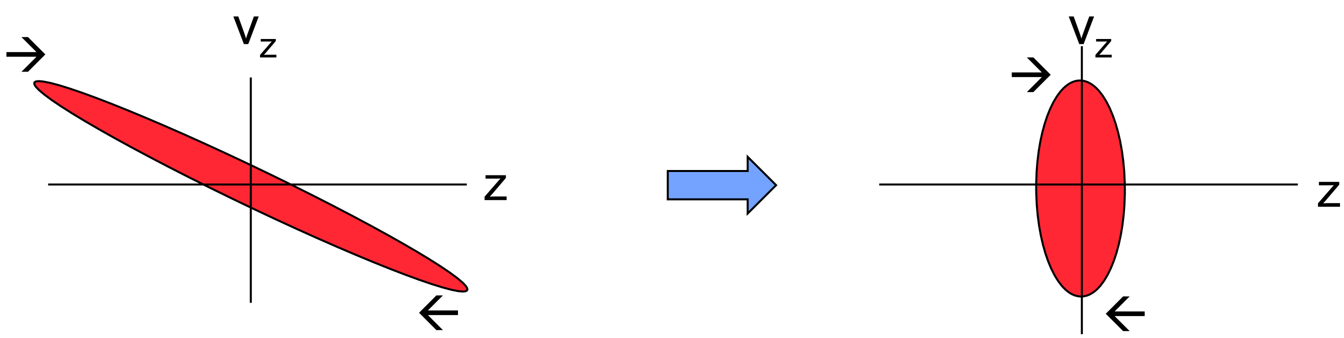
The drift compression process is used to shorten an ion bunch

- Induction cells impart a head-to-tail velocity gradient (“tilt”) to the beam
- The beam shortens as it “drifts” down the beam line

- In non-neutral drift compression, the space charge force opposes (“stagnates”) the inward flow, leading to a nearly mono-energetic compressed pulse:

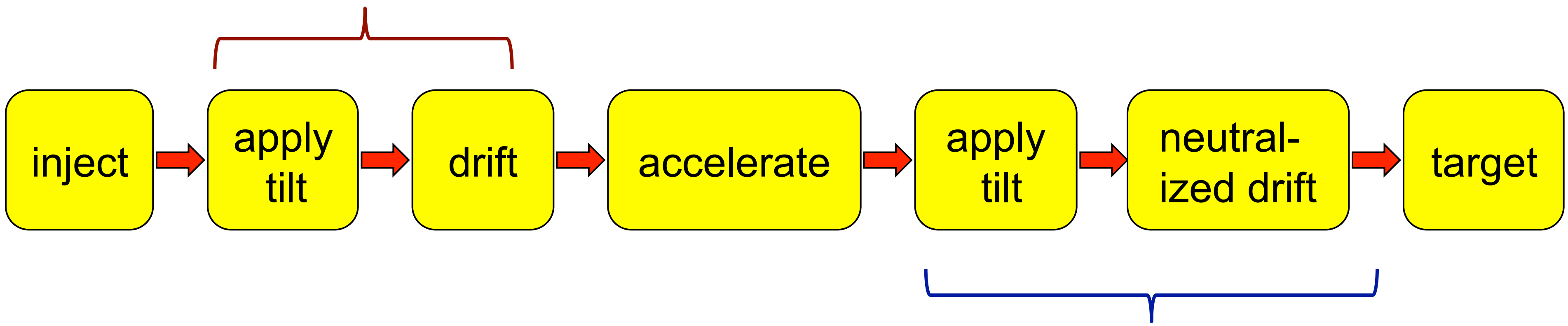


- In neutralized drift compression, the space charge force is eliminated, resulting in a shorter pulse but a larger velocity spread:



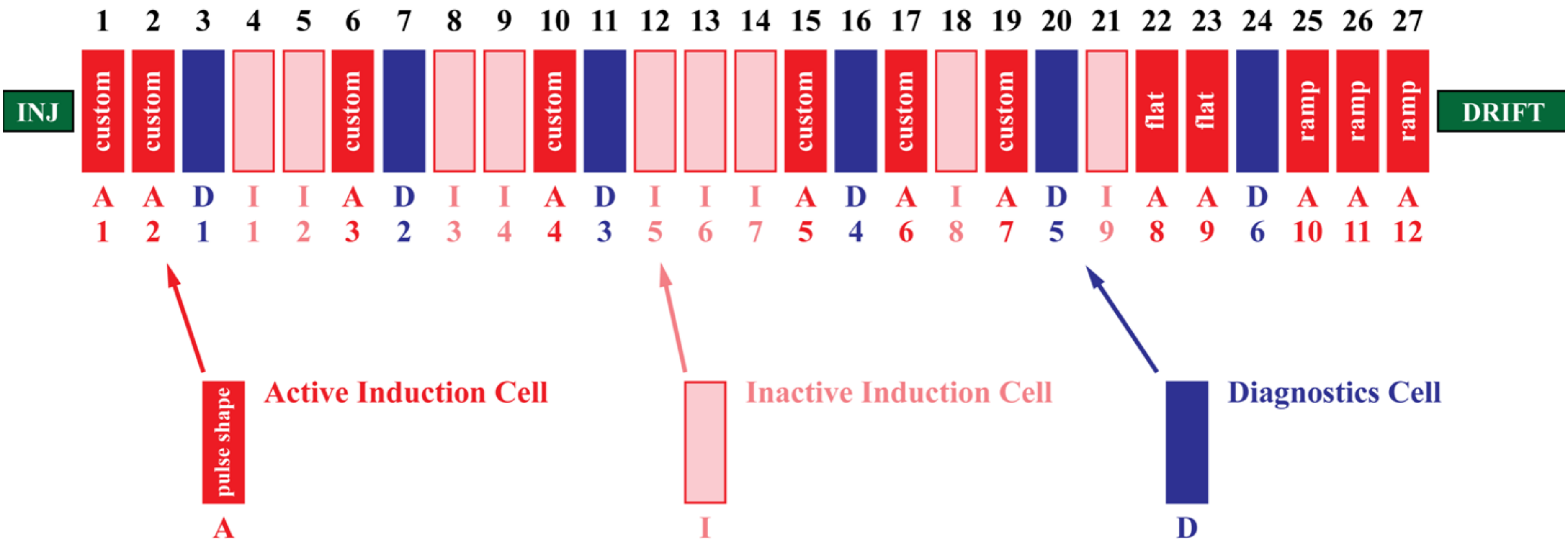
Drift compression is used twice in NDCX-II

Initial non-neutral pre-bunching for early use of 70-ns 250-kV Blumlein power supplies from ATA



Final neutralized drift compression onto the target

The baseline hardware configuration includes 27 cells,12 of which are “active” induction cells



- 27 lattice periods after the injector
- 12 active induction cells
- Beam charge ~50 nano-Coulombs
- FWHM < 1 ns
- Kinetic energy ~ 1.2 MeV

NDCX-II in April 2012

Space-charge-dominated ion beams are non-neutral plasmas

- For a beam in an accelerator to be near equilibrium, it must be in (time-averaged) transverse force balance.
  - Usually, the beam's thermal pressure ("emittance") and the applied confining forces are the large terms, with space charge a perturbation.
  - In our beams, the primary balance is between space-charge repulsion and the confining forces; thermal pressure is modest, flow is quasi-laminar.
- "Generalized perveance" is space charge potential energy / beam k.e.:

$$K = \frac{2q\lambda}{4\pi\varepsilon_0 m v^2}$$

  - Almost all beams have modest K; e.g., the GSI RFQ has K ~ 4×10^{-6}.
  - Our beams usually have K's of 10^{-4} - 10^{-3}.
  - NDCX-II has a peak K of 10^{-2}; we must confine it steadily with solenoids

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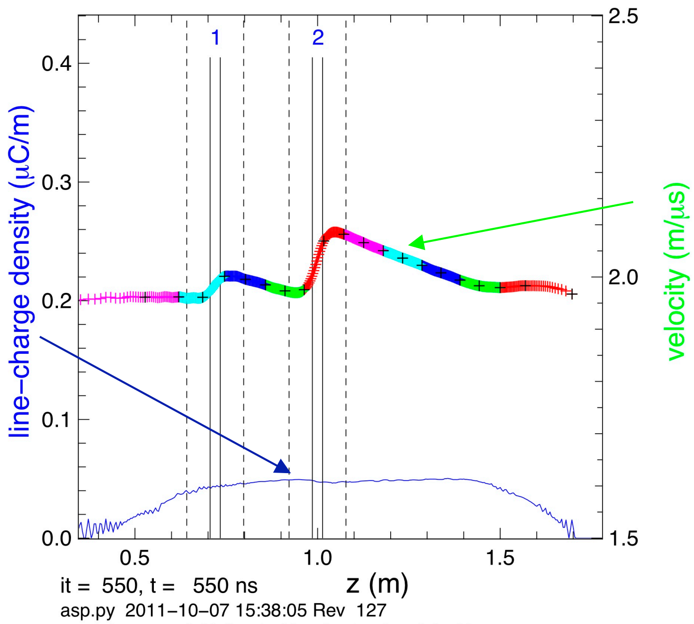
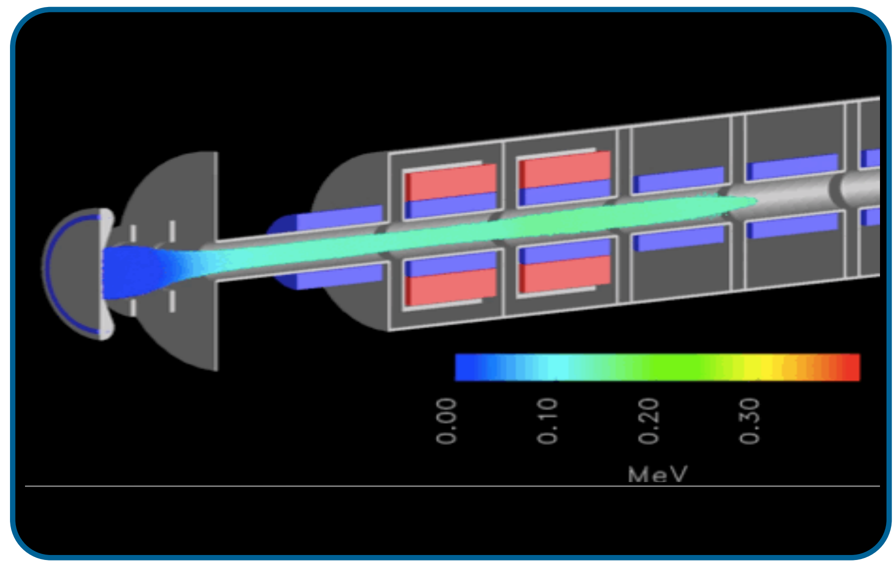
- These beams are collisionless ("long memory"), & exhibit collective behaviors
- They must be simulated, and analyzed, using the techniques of plasma physics (*e.g.*, particle-in-cell simulations, Vlasov equation).

Simulation tools capture the beam dynamics; these enabled the NDCX-II physics design

- ASP is a fast 1-D PIC code
  - follows (z,vz) phase space using a few hundred particles
  - tracks centroid for studying misalignments
  - optimization capabilities
  - interactive (Python+Fortran)

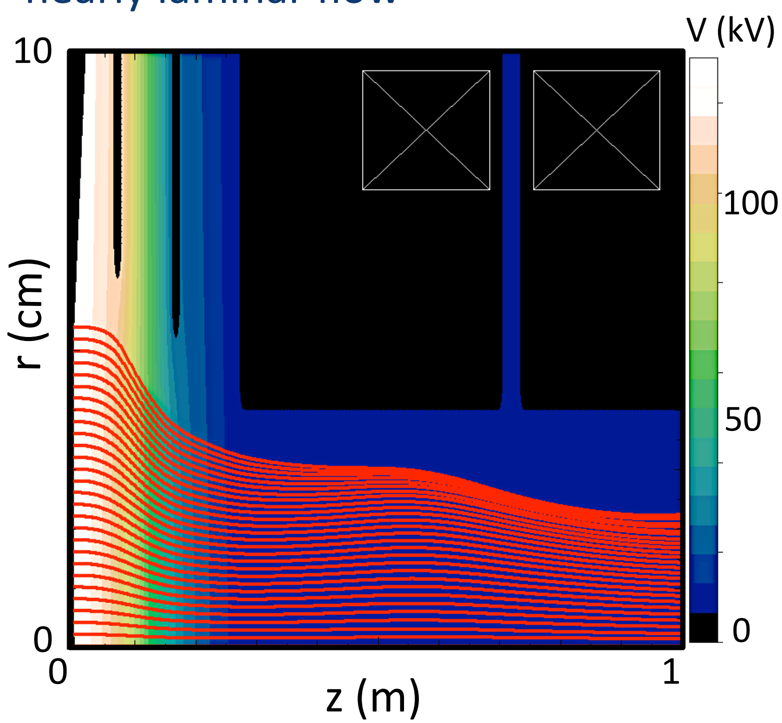


- Warp is our full-physics PIC code
  - 1, 2, and 3-D ES and EM fields
  - models of accelerator "lattice" components
  - models of particle injection, interactions
  - innovative capabilities



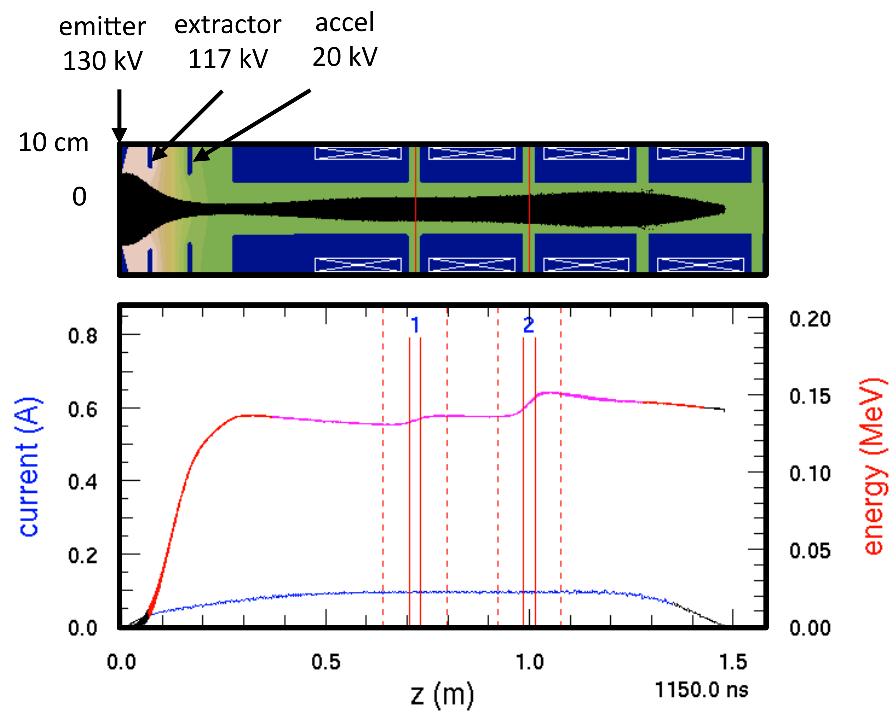
Steps in development of the NDCX-II physics design …

first, use Warp steady-flow "gun" mode to design the injector for a nearly laminar flow



1 mA/cm^2 Li$^+$ ion source

second, carry out a time-dependent *r-z* simulation from the source with Warp



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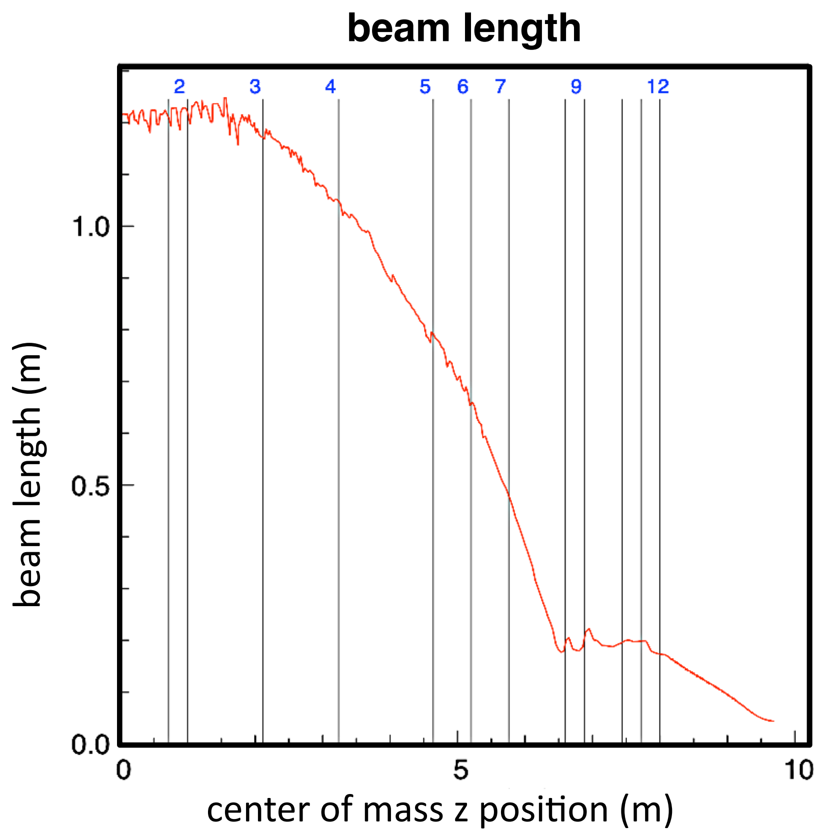
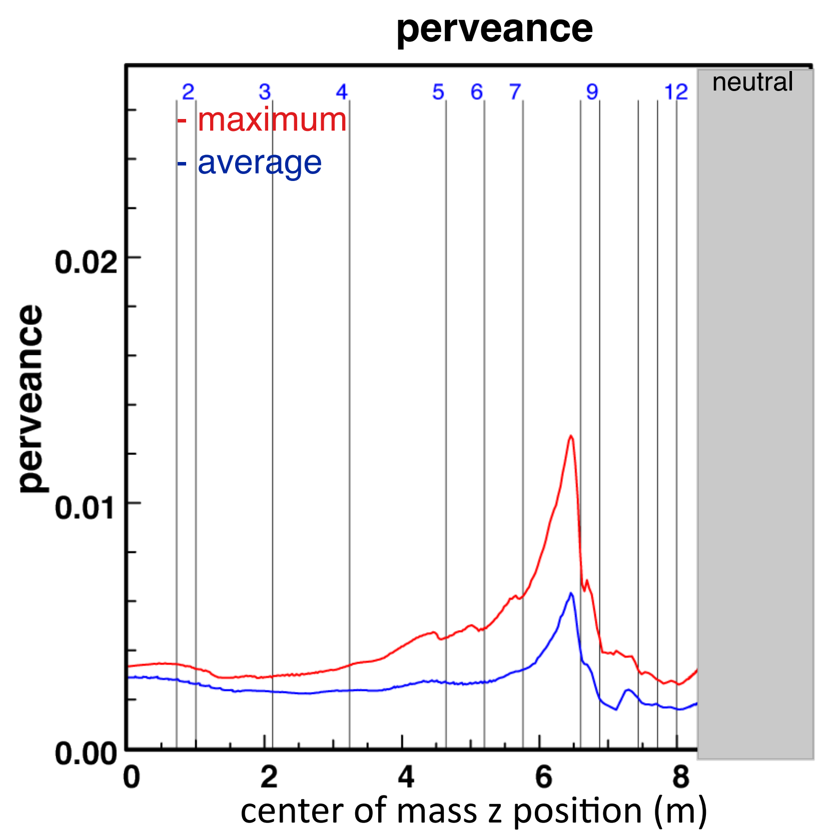
Steps in development of the NDCX-II physics design …

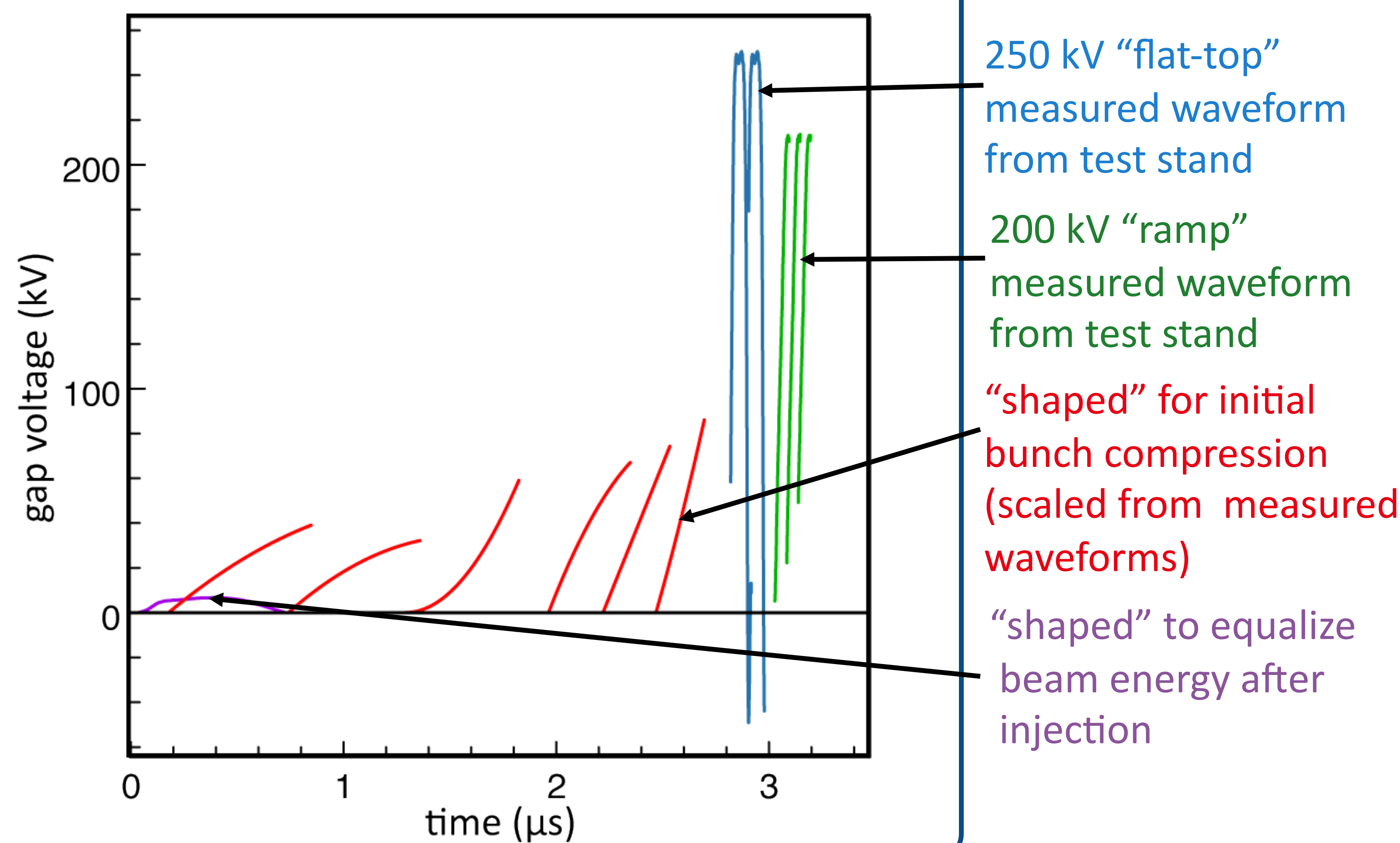
third, iterate with ASP to find an acceleration schedule that delivers a beam with a desirable final phase-space distribution





Steps in development of the NDCX-II physics design …

fourth, pass the waveforms back to Warp and verify with time-dependent *r-z* simulation



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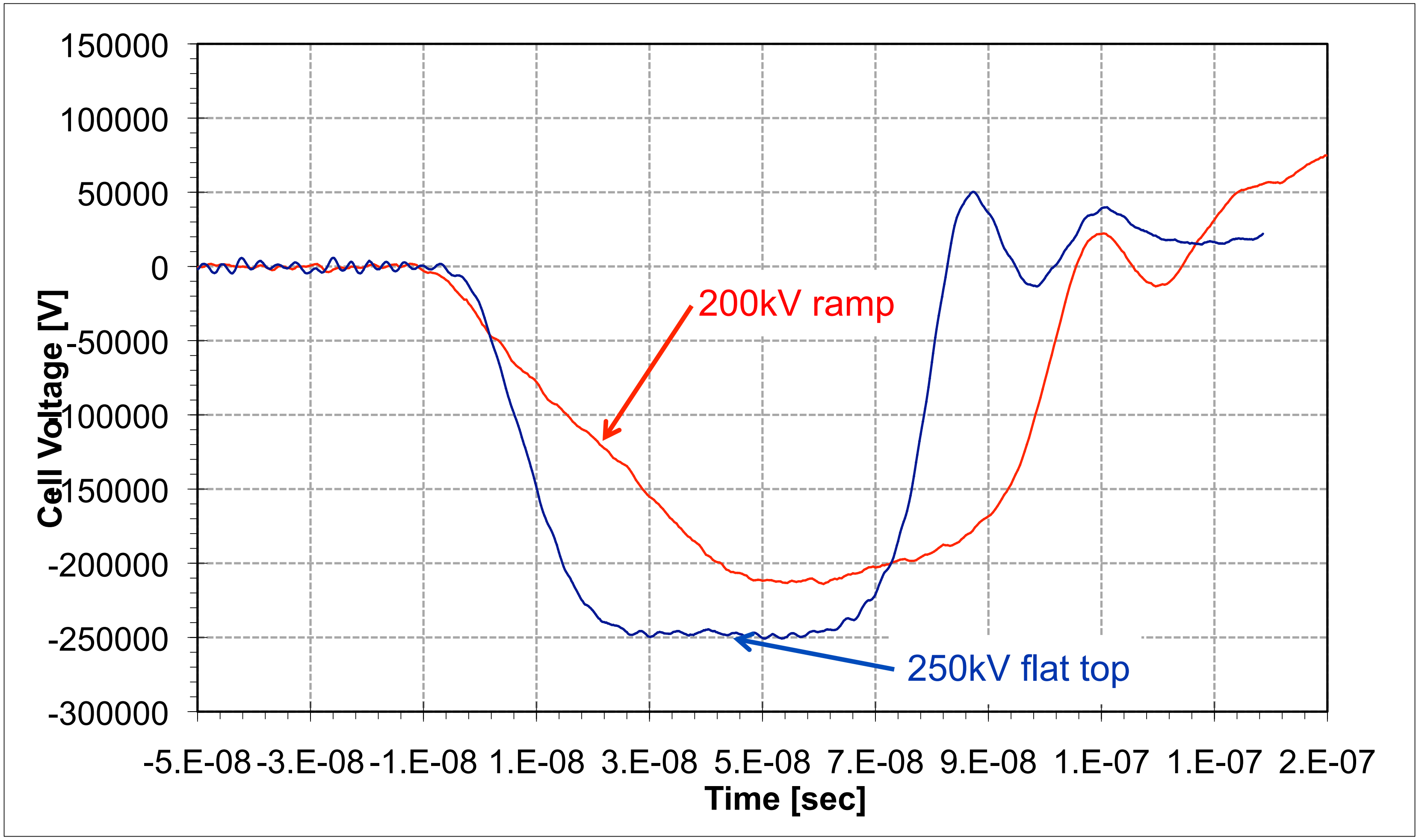
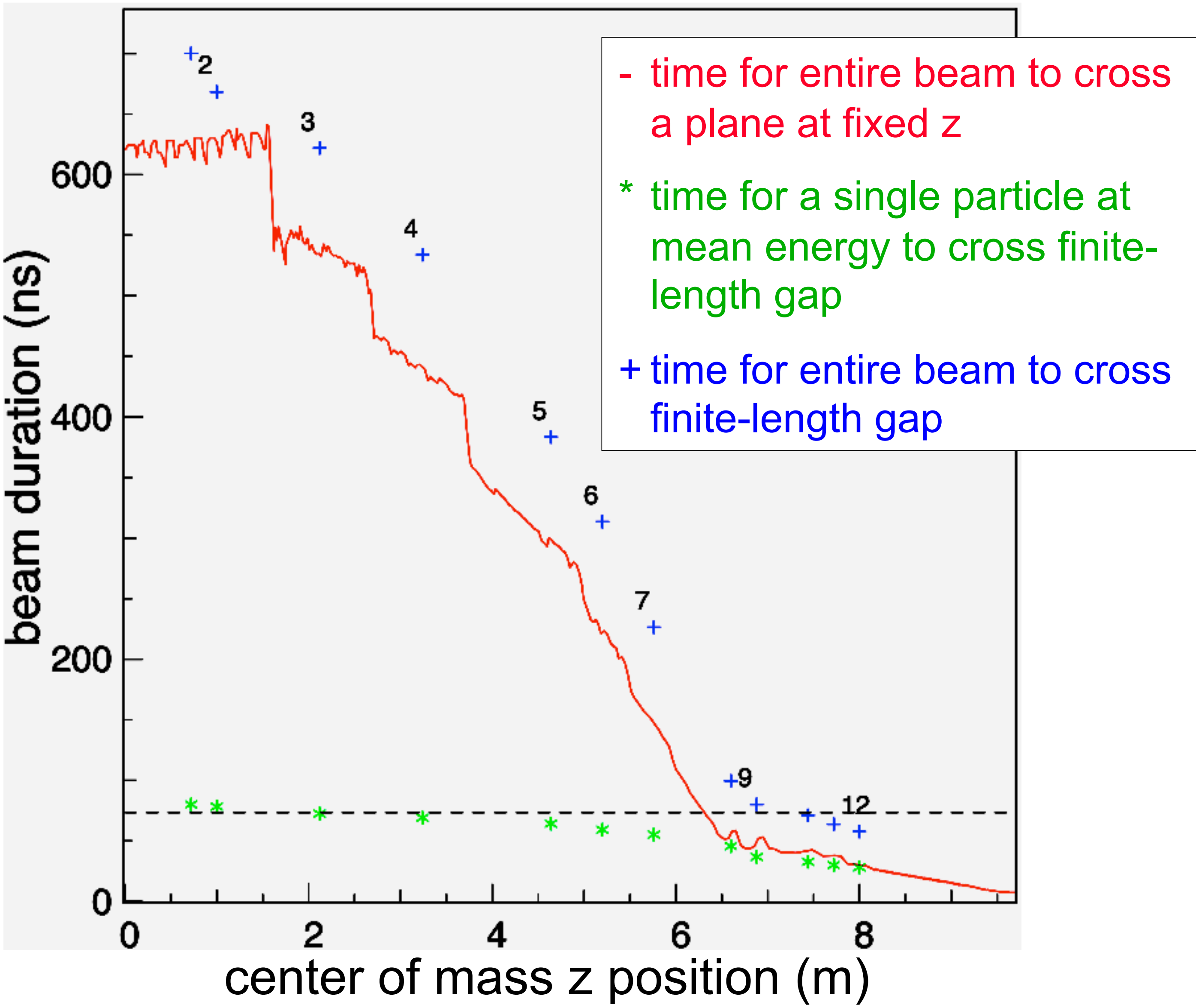
Flat top and ramped voltage waveforms generated on the test stand were used in the physics design



Pulse duration vs. z: the finite length of the gap field folds in



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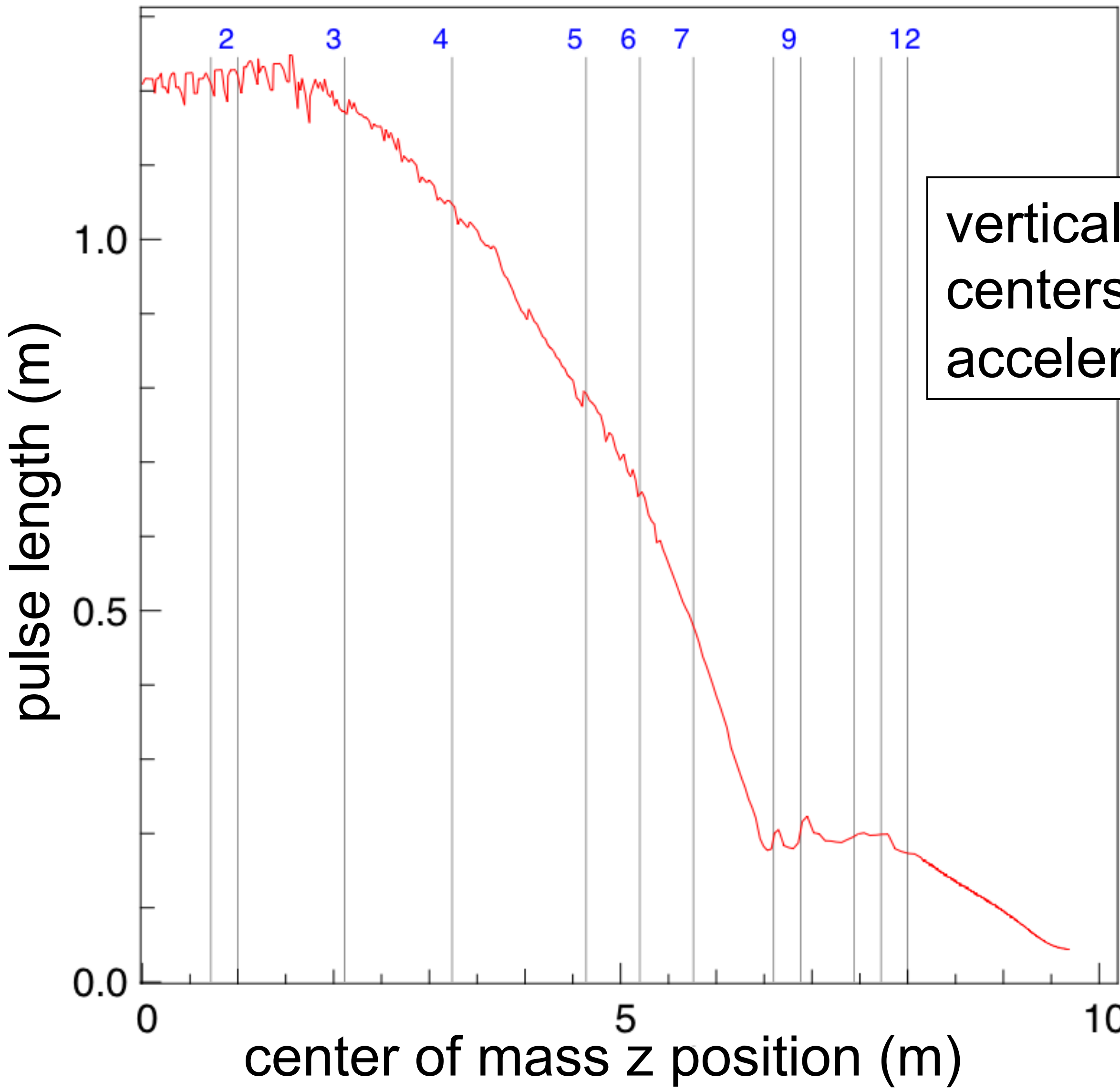
Pulse length vs. z, as developed using 1-D ASP simulation



vertical lines denote centers of active acceleration gaps

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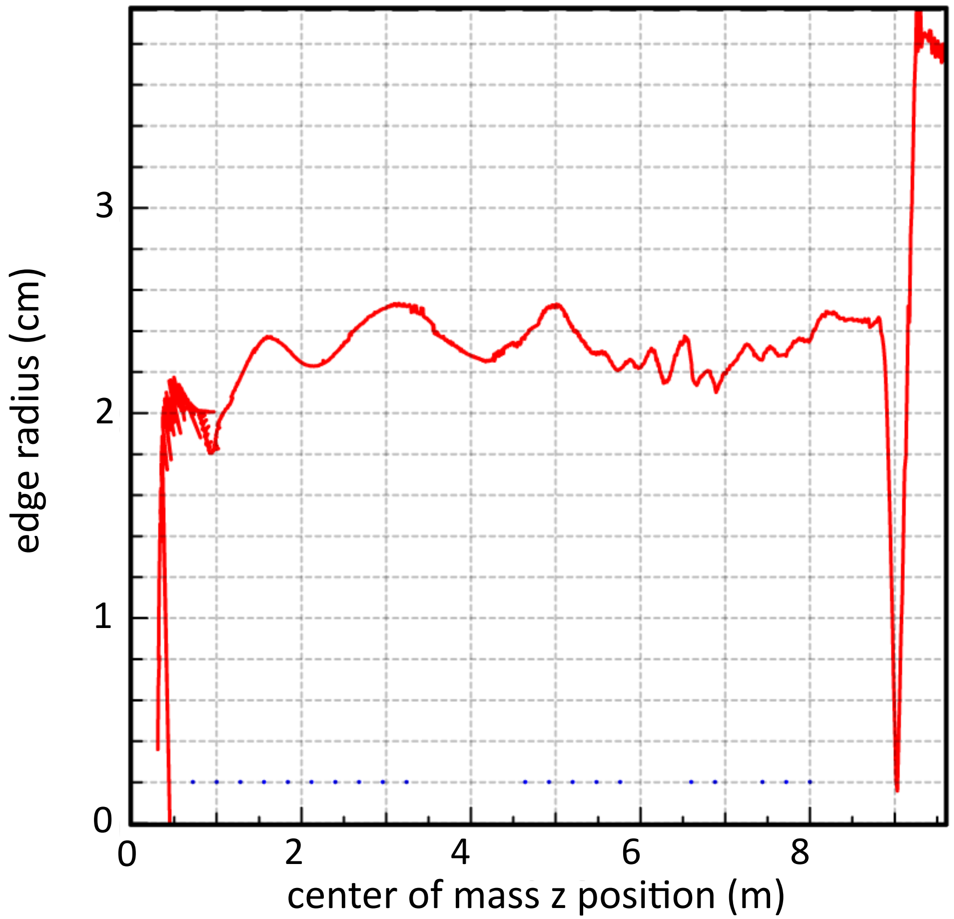
Steps in development of the NDCX-II physics design …

fifth, adjust transverse focusing to maintain nearly constant radius



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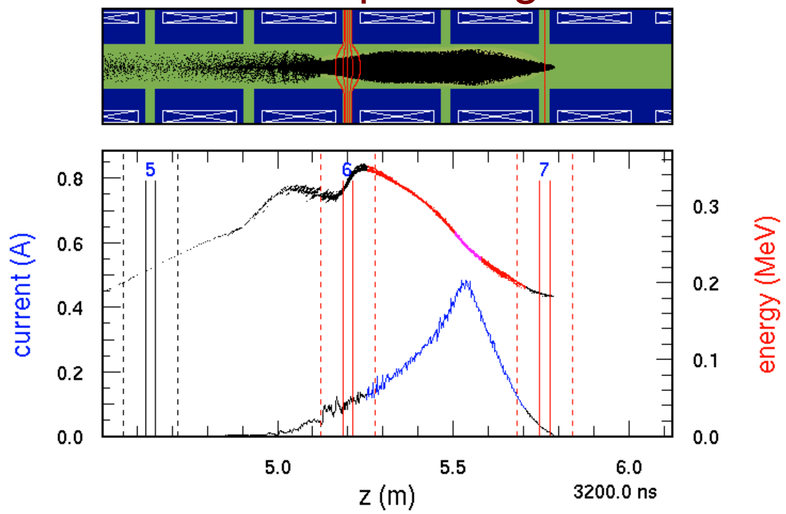
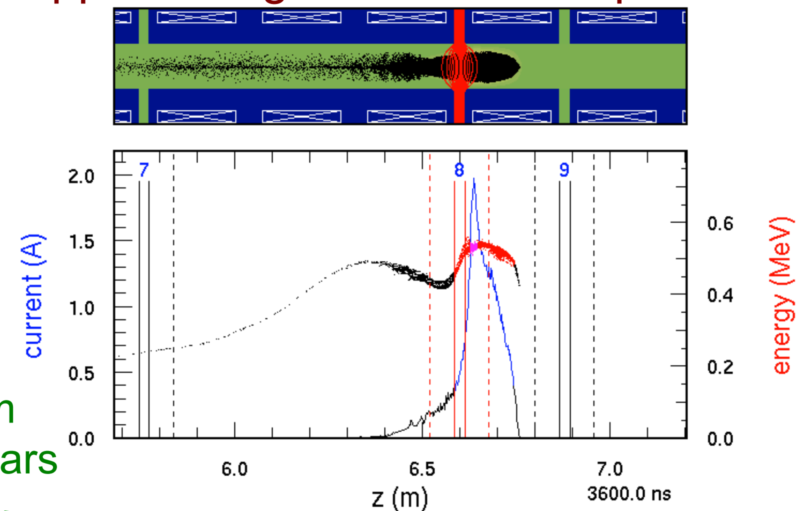
Snapshots from a Warp (r,z) simulation

compressing

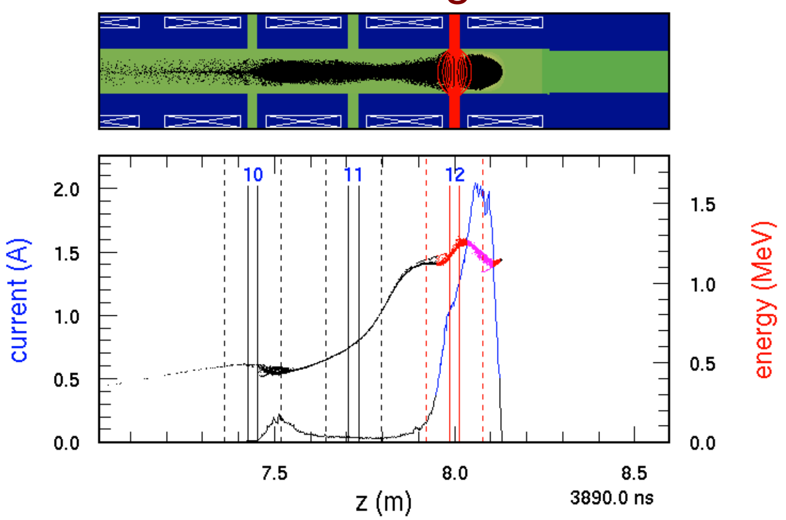


approaching maximum compression

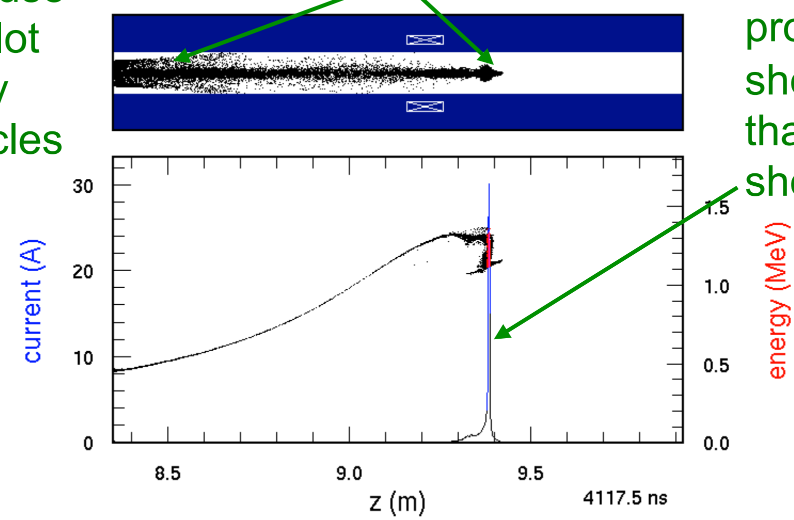


Beam appears long because we plot many particles …

exiting



at focus



… but current profile shows that it is short

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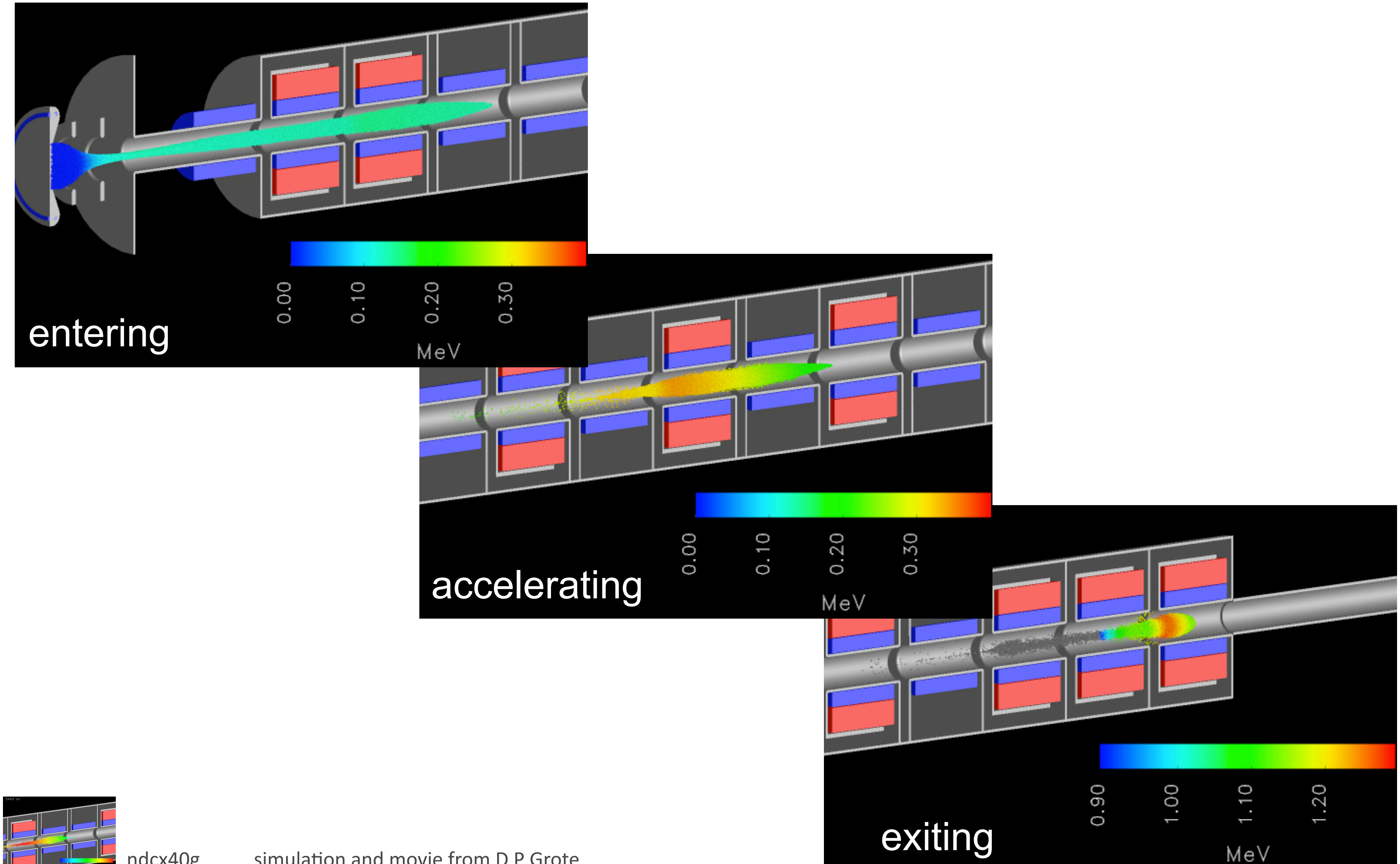
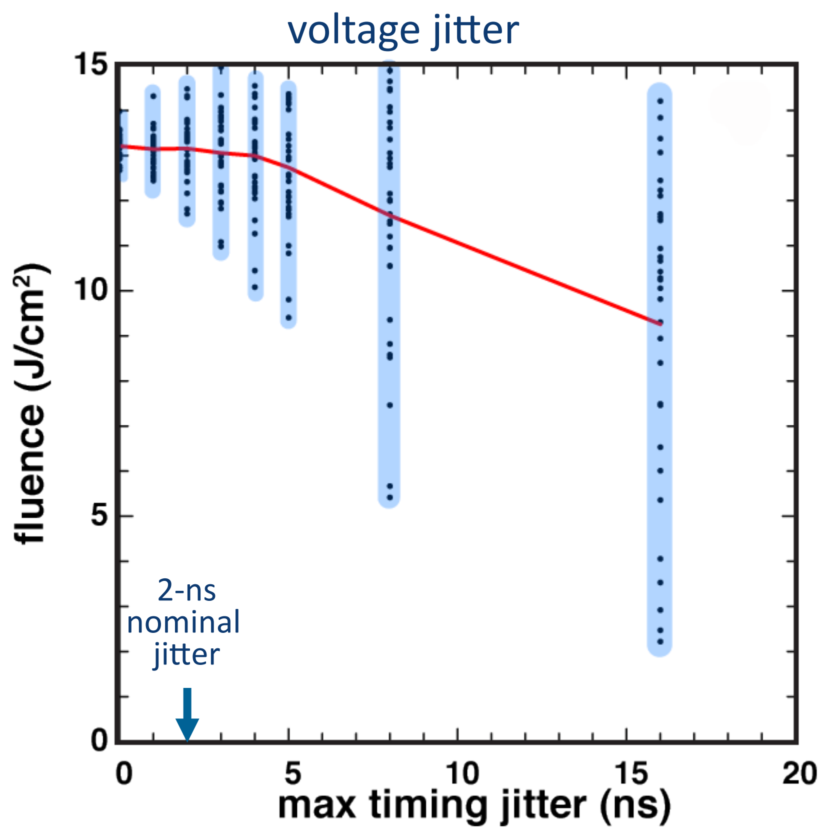
3-D Warp simulation with perfectly aligned solenoids



ndcx40g simulation and movie from D P Grote

Steps in development of the NDCX-II physics design …

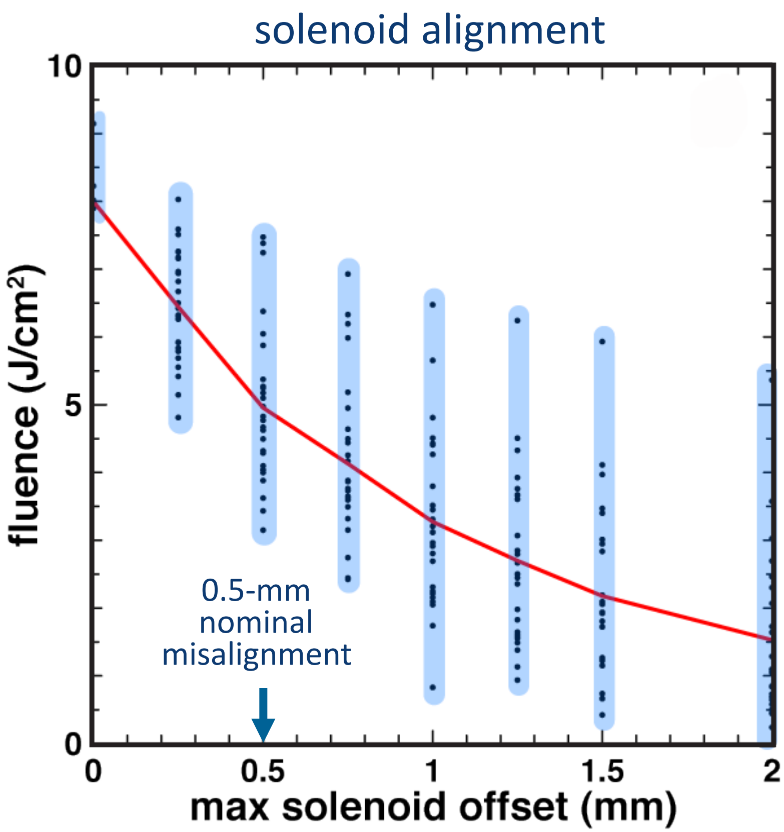
sixth, test sensitivity to random timing error in acceleration waveforms



40g-12 with random timing shifts in acceleration voltage pulses

Steps in development of the NDCX-II physics design …

seventh, test sensitivity to random solenoid misalignments

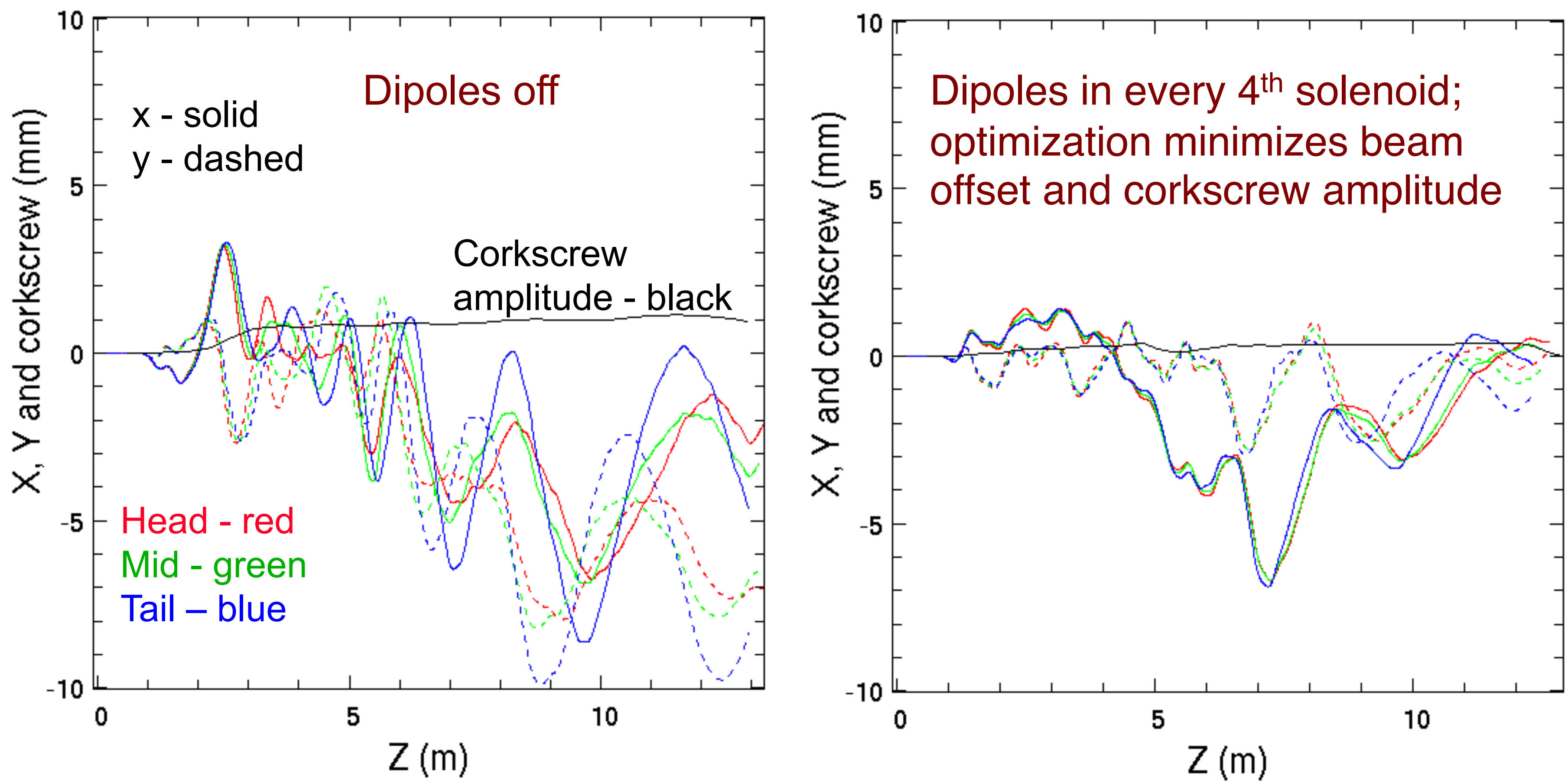


40g-12 with random offsets to both ends of each solenoid

Beam "steering" via dipole magnets will center beam and minimize "corkscrew" distortion.

To assess steering, we again used the fast ASP code; a tuning algorithm (as in ETA-II, DARHT)‡ adjusts dipole strengths

Trajectories of head, mid, tail particles, and corkscrew amplitude, for a 34-cell ASP run. Random offsets of solenoid ends up to 1 mm were assumed; the effect is linear.



‡ Y-J. Chen, Nucl. Instr. and Meth. A **398**, 139 (1997).

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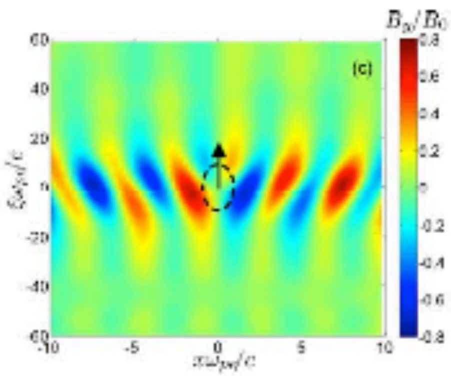
NDCX-II will enable greater understanding of beams in plasmas

Electromagnetic fields are excited by a moving beam in a magnetized plasma:

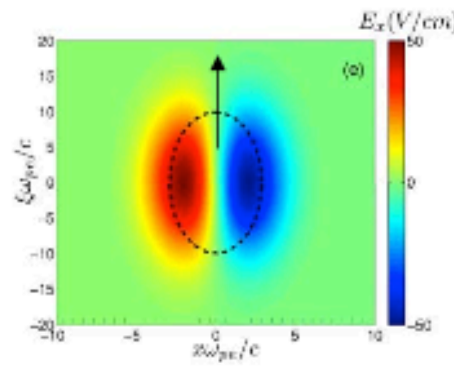
Wave field (can extend far outside the bunch)



Can be used for diagnostics

M. Dorf, I. Kaganovich, E. Startsev, and R. C. Davidson, Phys. Plasmas **17**, 023103 (2010).

Local field (falls off rapidly outside the bunch)



Can provide bunch focusing

M. Dorf, I. Kaganovich, E. Startsev, and R. C. Davidson, PRL **103**, 075003 (2009)

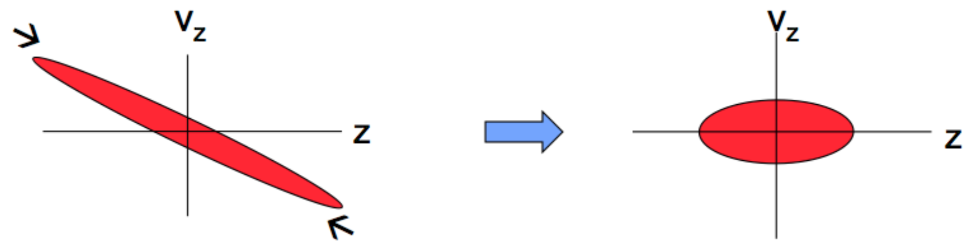
Review paper: I. D. Kaganovich, *et al.*, Phys. Plasmas **17**, 056703 (2010)

NDCX-II will be an exciting platform for beam physics studies (many of them relevant to an HIF driver)

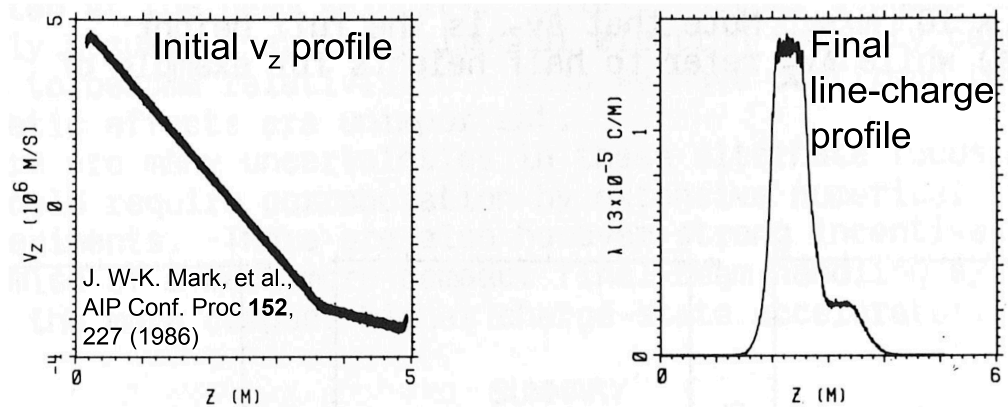
- NDCX-II operation embodies collective beam dynamics:
  - Space-charge force (“perveance”) is very large
  - Driver-like compression of non-neutral and neutralized beams
  - Removal of velocity tilt by space-charge force, to achieve “stagnation”
  - Longitudinal waves are evident
- Non-ideal effects include:
  - Emittance growth (phase-space dilution), “halo” formation
  - Beam - plasma interactions and instabilities
  - Aberrations in final focus
- Add-on hardware could enable studies of:
  - Collective focusing of ion beams
  - Intense beam transport in quadrupoles
  - Beam dynamics in bends
- Beam diagnostics will be developed and improved

HIF-relevant beam experiments on NDCX-II can study …

- How well can space charge "stagnate" the compression to produce a "mono-energetic" beam at the final focus?



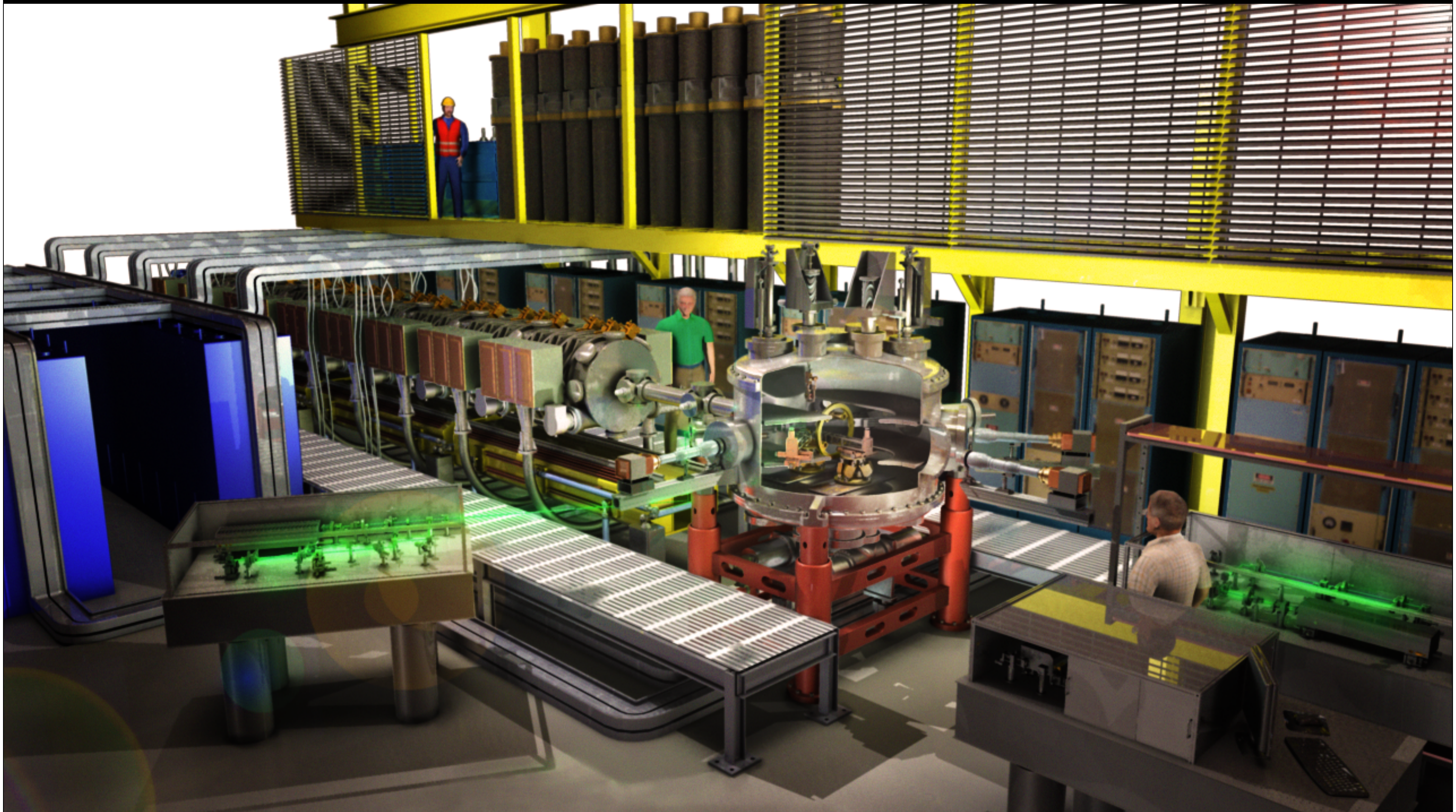
- How well can we pulse-shape a beam during drift compression (vs. the Robust Point Design's "building blocks")?



- How well can we compress a beam while bending it?:
  - "achromatic" design, so that particles with all energies exit bend similarly
  - or, leave some chromatic effect in for radial zooming
  - emittance growth due to dispersion in the bend
- Are there any issues with final focus using a set of quadrupole magnets?

Most dimensionless parameters (perveance, "tune depression," compression ratio, etc.) will be similar to, or more aggressive than, those in a driver.

NDCX-II will be a unique user facility for warm dense matter, IFE target physics, and intense-beam physics.



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