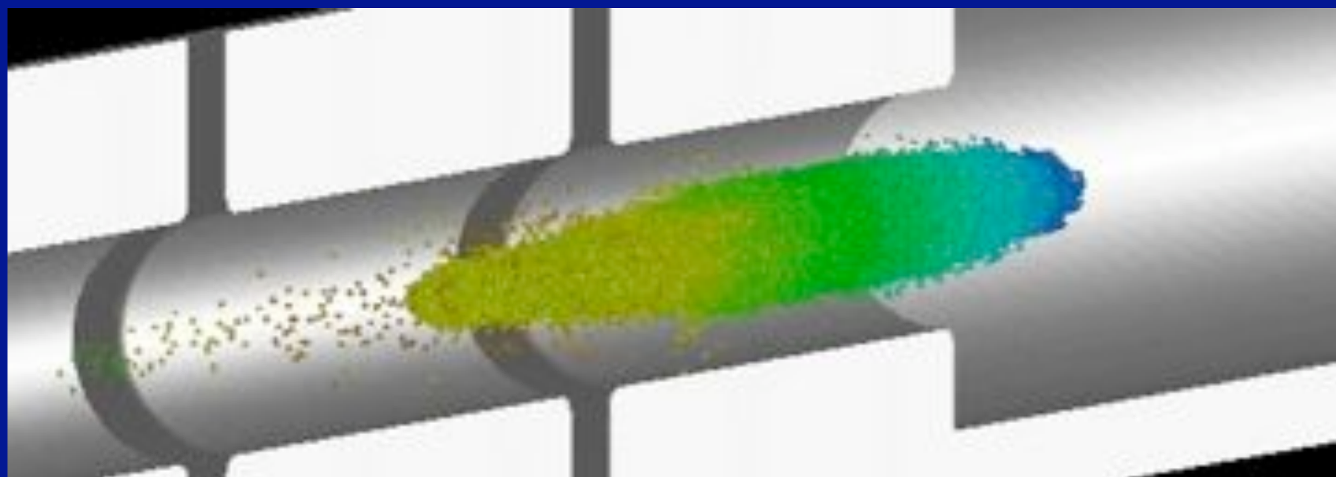
Physics Design for NDCX-II, A Short-pulse Ion Beam Driver for Near-term WDM and Target Physics Studies*



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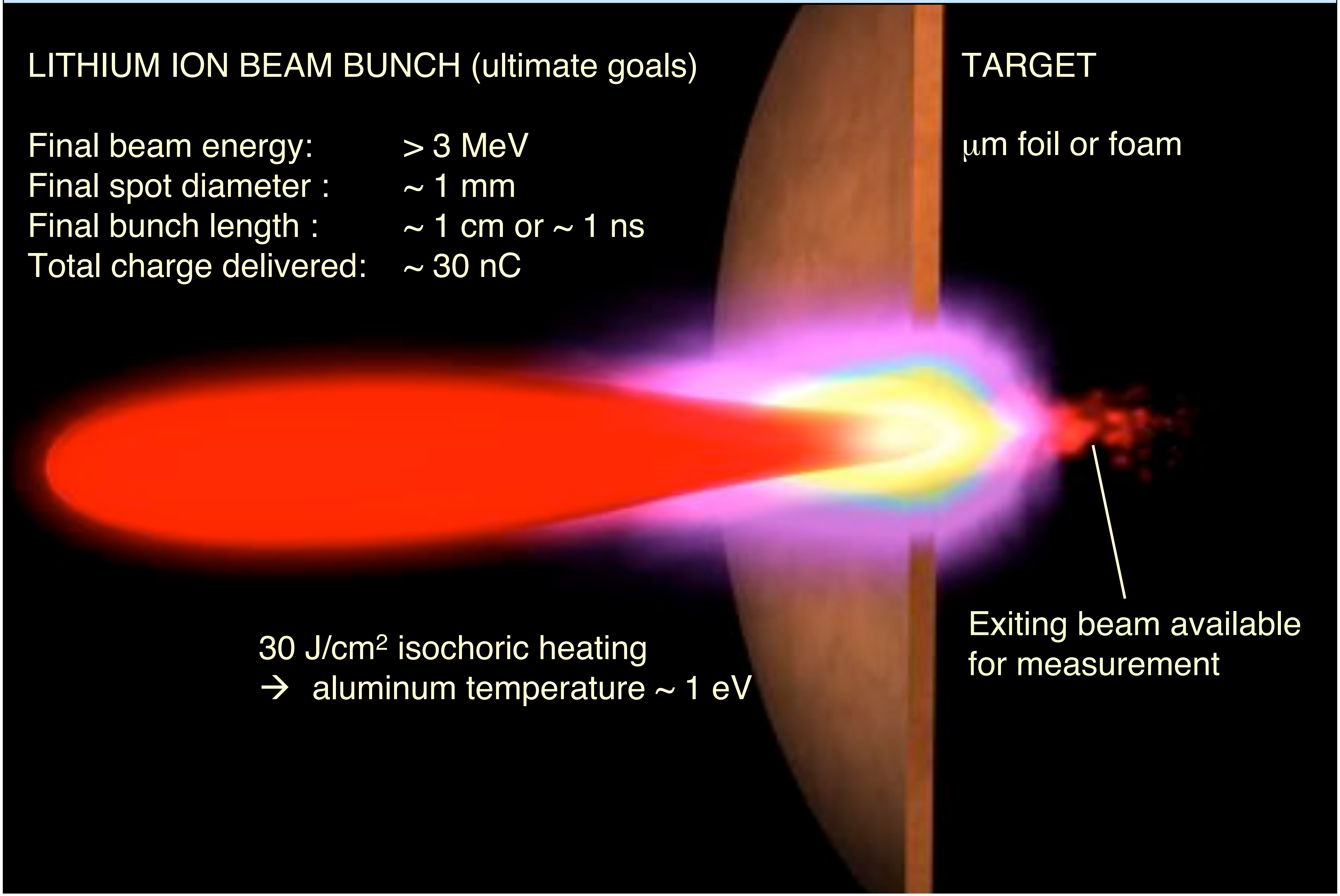
Heavy Ion Fusion Science Virtual National Laboratory

Outline

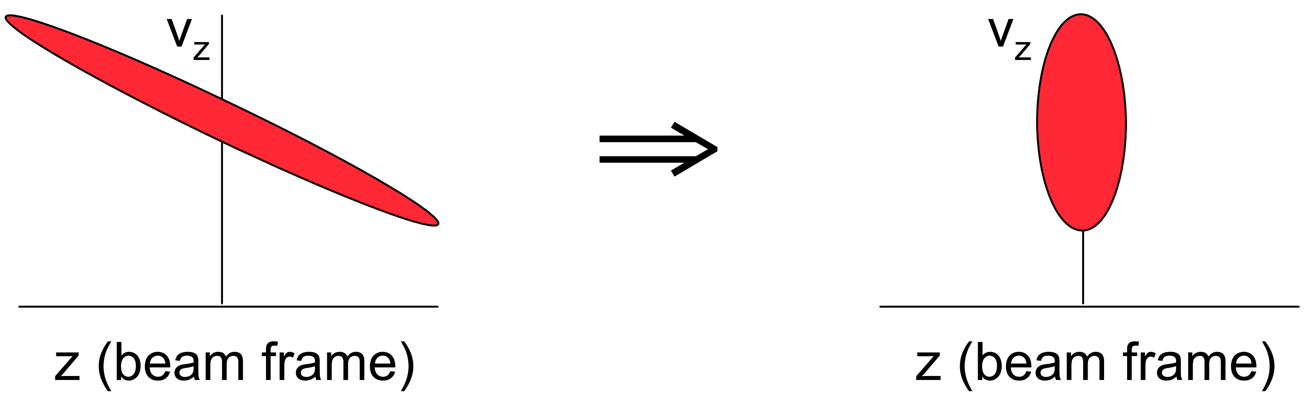
- Introduction to the project
- 1-D ASP code model and physics design
- Warp (R,Z) simulations
- 3-D effects: misalignments & corkscrew
- Status of the design

NDCX-II will enable studies of warm dense matter *and* key physics for ion direct drive



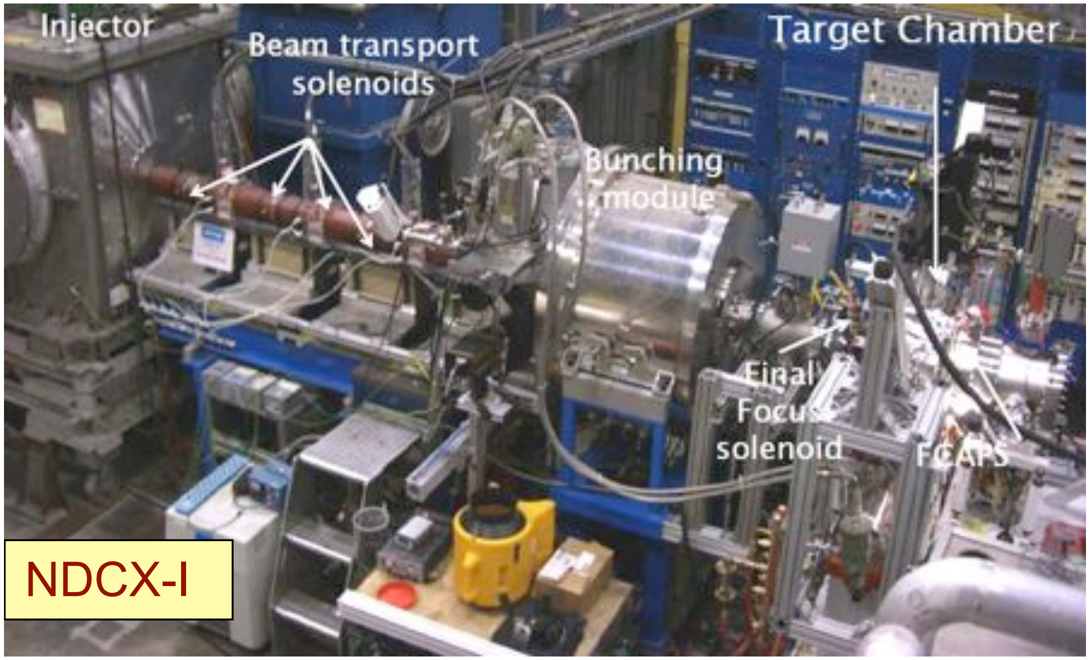
“Neutralized Drift Compression” produces a short pulse of ions

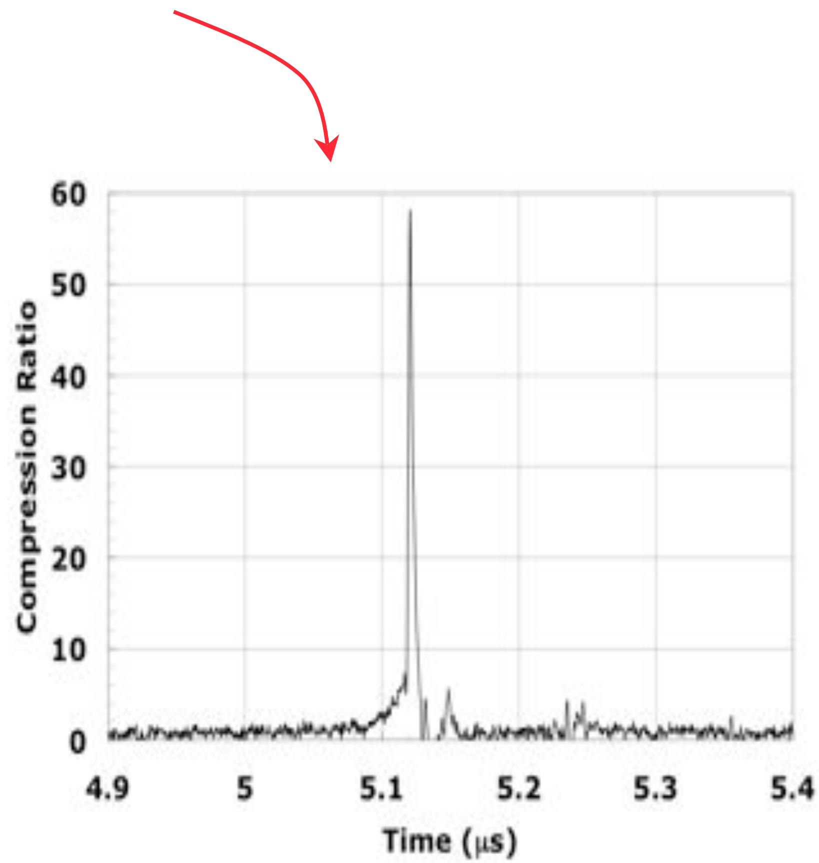
- The process is analogous to “chirped pulse amplification” in lasers
- A head-to-tail velocity gradient (“tilt”) is imparted to the beam by one or more induction cells
- This causes the beam to shorten as it moves down the beamline:



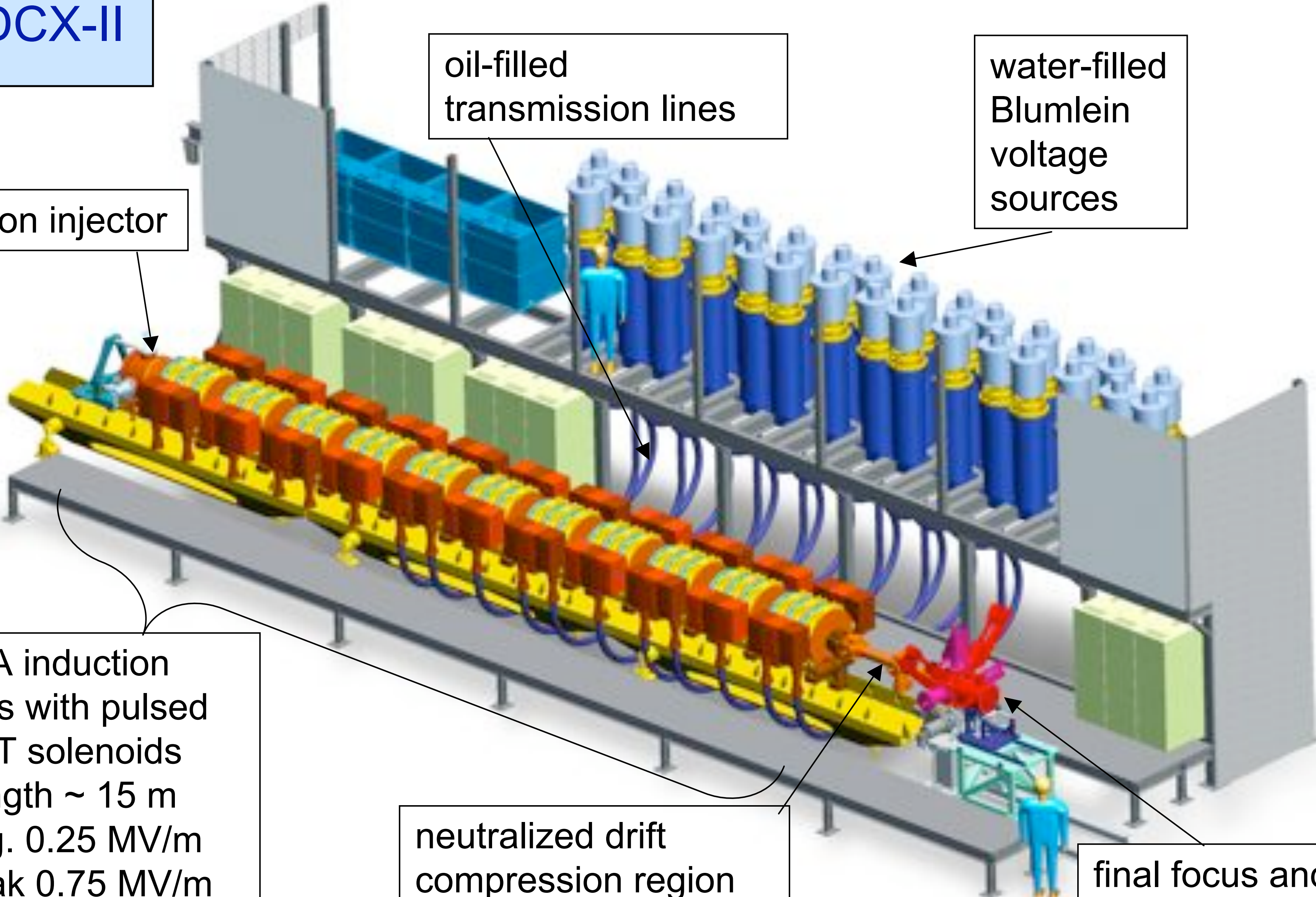
- Space charge would inhibit this compression, so the beam is directed through a plasma which affords neutralization
- Simulations and theory (Voss Scientific, PPPL) showed that the plasma density must exceed the beam density for this to work well

NDCX-I at LBNL routinely achieves current amplification > 50x





NDCX-II

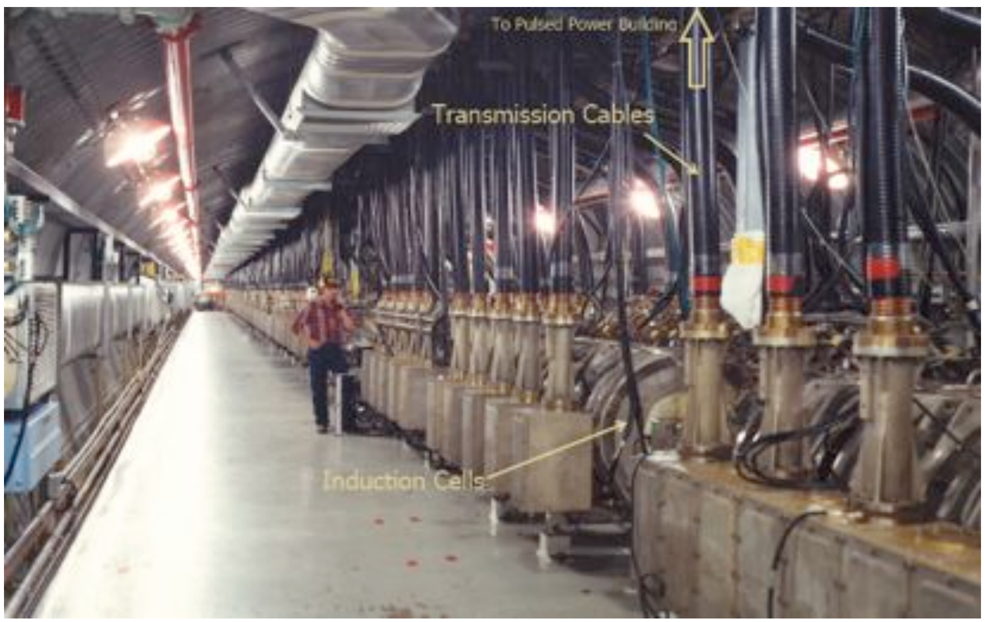


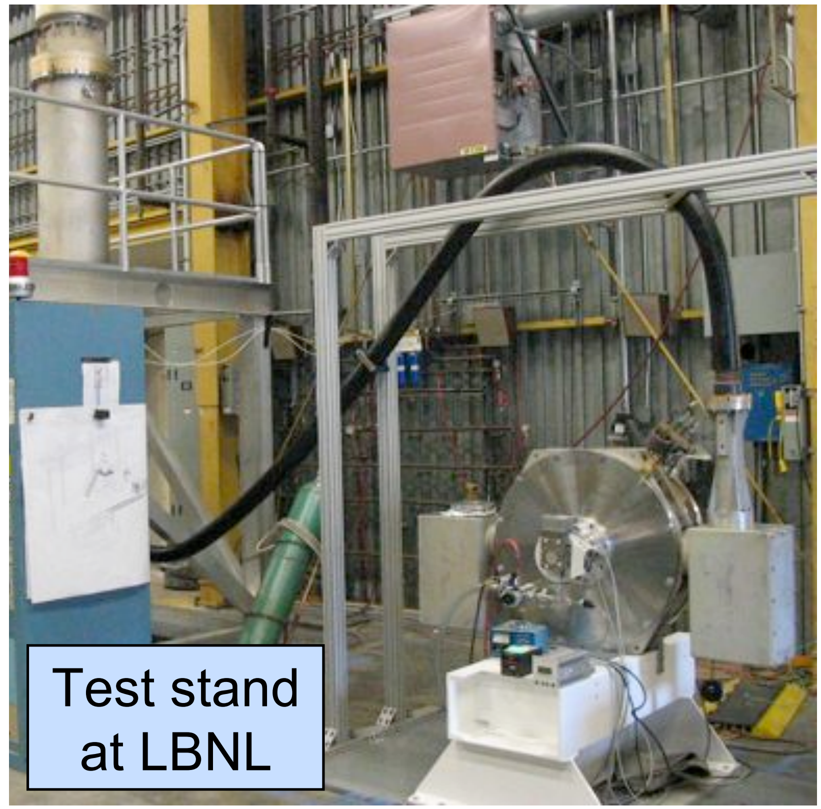
oil-filled transmission lines
water-filled Blumlein voltage sources
Li⁺ ion injector
ATA induction cells with pulsed 1-3T solenoids
Length ~ 15 m
Avg. 0.25 MV/m
Peak 0.75 MV/m
neutralized drift compression region with plasma sources
final focus and target chamber

LLNL has given the HIFS-VNL 48 induction cells from the ATA

- They provide short, high-voltage accelerating pulses
  - Ferrite core: 1.4 x 10^{-3} Volt-seconds
  - Blumlein: 200-250 kV; 70 ns FWHM
- At front end, longer pulses need custom voltage sources; < 100 kV for cost

Advanced Test Accelerator (ATA)





Test stand at LBNL

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1-D PIC code ASP ("Acceleration Schedule Program")

- Follows (z,v_z) phase space using a few hundred particles ("slices")
- Space-charge field via Poisson equation with finite-radius correction term

$$\nabla^2\phi \;\approx\; d^2\phi/dz^2 - k_\perp^2\,\phi \;=\; -\,\rho/\varepsilon_0$$

$$k_\perp^2 = 4 \,/\, (g_0\, r_{beam}^2) \qquad\qquad g_0 = 2 \log\,(r_{wall} \,/\, r_{beam})$$

- Acceleration gaps with longitudinally-extended fringing field
  - Idealized waveforms
  - Circuit models including passive elements in "comp boxes"
  - Measured waveforms
- Centroid tracking for studying misalignment effects, steering
- Multiple optimization loops:
  - Waveforms and timings
  - Dipole strengths (for steering)
- Interactive (Python language with Fortran for intensive parts)

Principle 1: Shorten Beam First ("non-neutral drift compression")

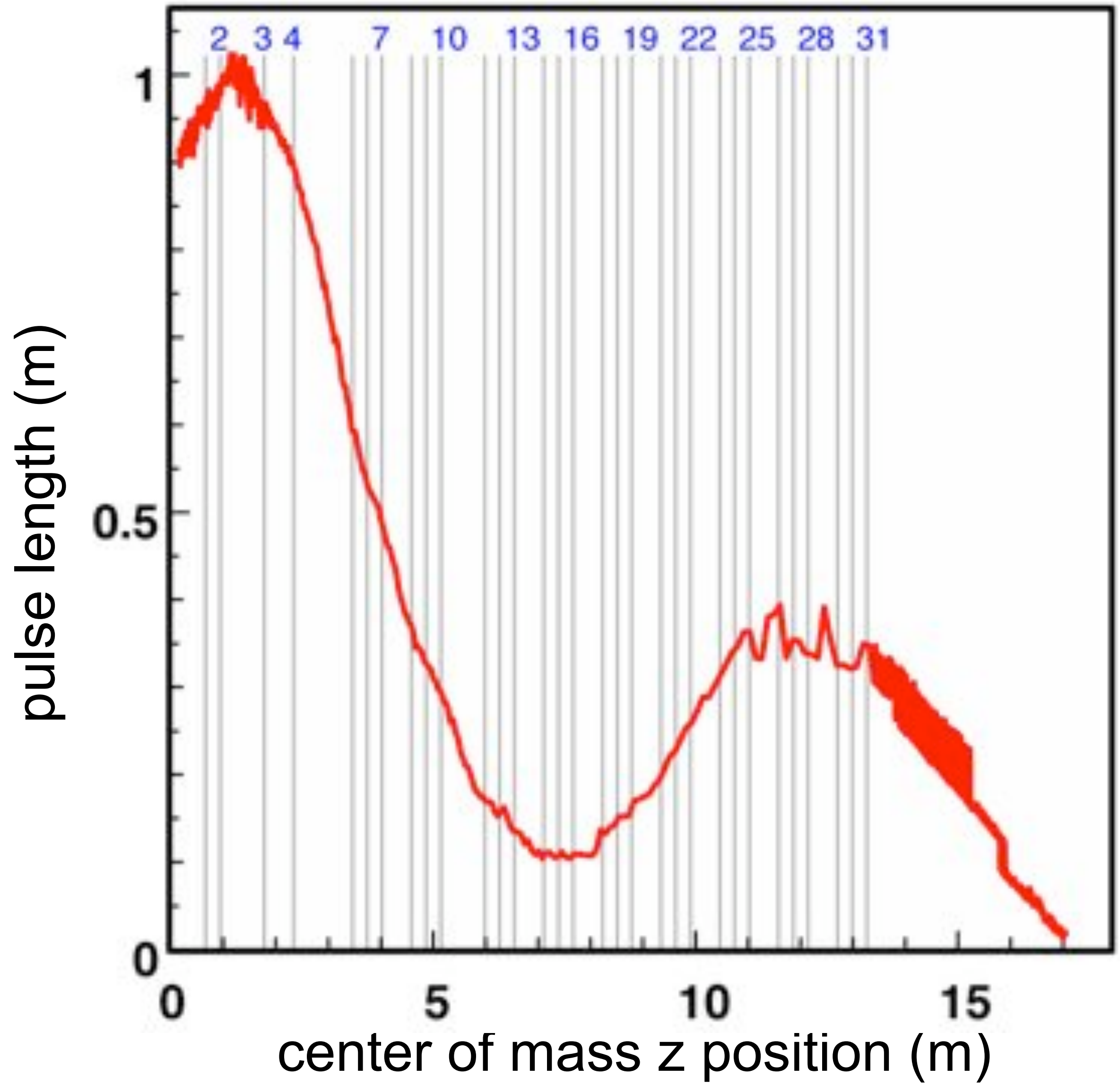
- Equalize beam energy after injection -- then --
- Compress longitudinally before main acceleration
- Want < 70 ns transit time through gap (with fringe field) as soon as possible

  ==> can then use 200-kV pulses from ATA Blumleins
- Compress carefully to minimize effects of space charge
- Seek to achieve large velocity "tilt" $v_z(z)$ ~ linear in z "right away"

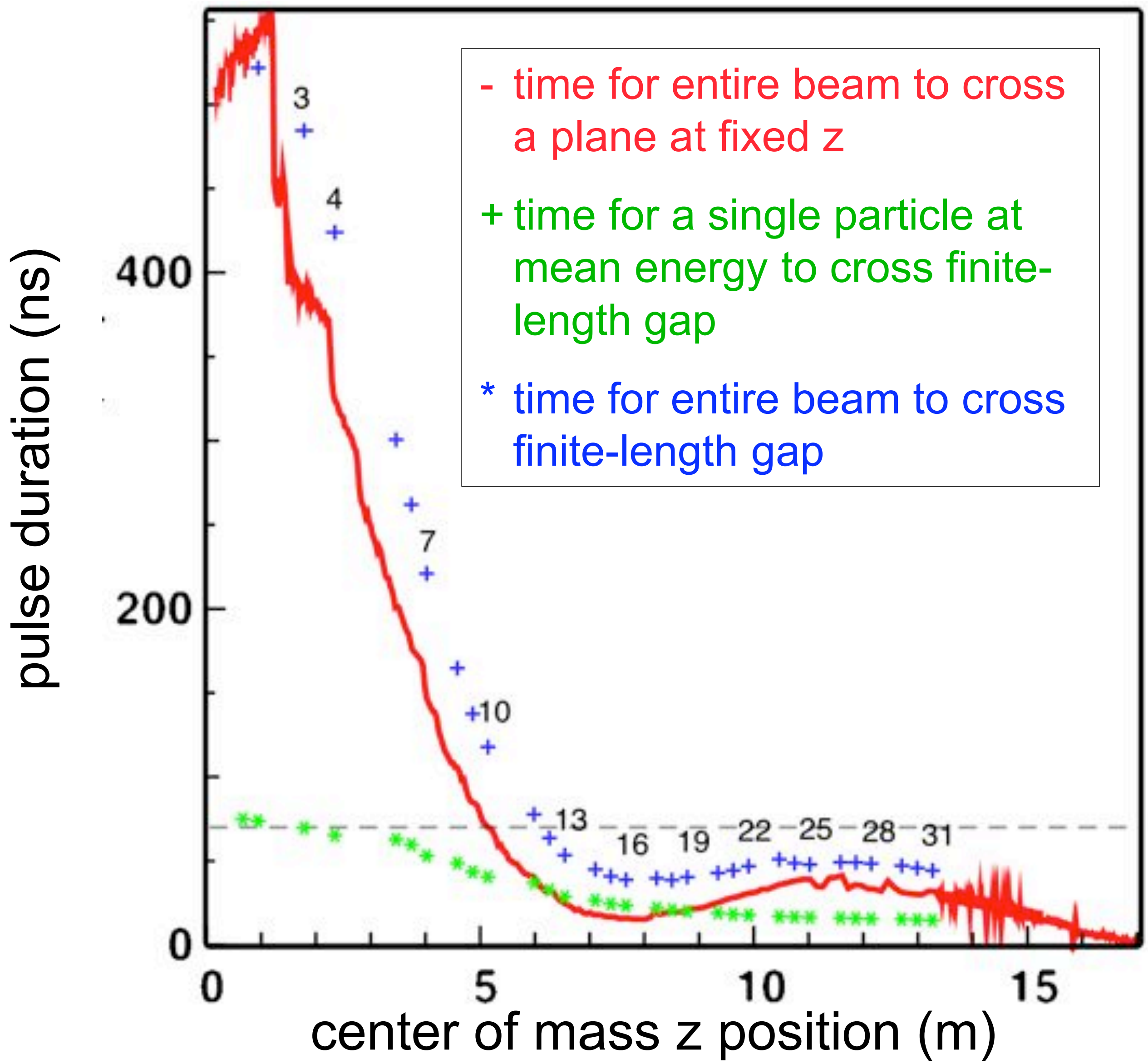
Principle 2: Let It Bounce

- Rapid inward motion in beam frame is required to get below 70 ns
- Space charge ultimately inhibits this compression
- However, so short a beam is not sustainable
  – Fields to control it can't be "shaped" on that timescale
  – The beam "bounces" and starts to lengthen
- Fortunately, the beam still takes < 70 ns because it is now moving faster
- We allow it to lengthen while applying:
  – additional acceleration via flat pulses
  – confinement via ramped ("triangular") pulses
- The final few gaps apply the "exit tilt" needed for neutralized drift compression

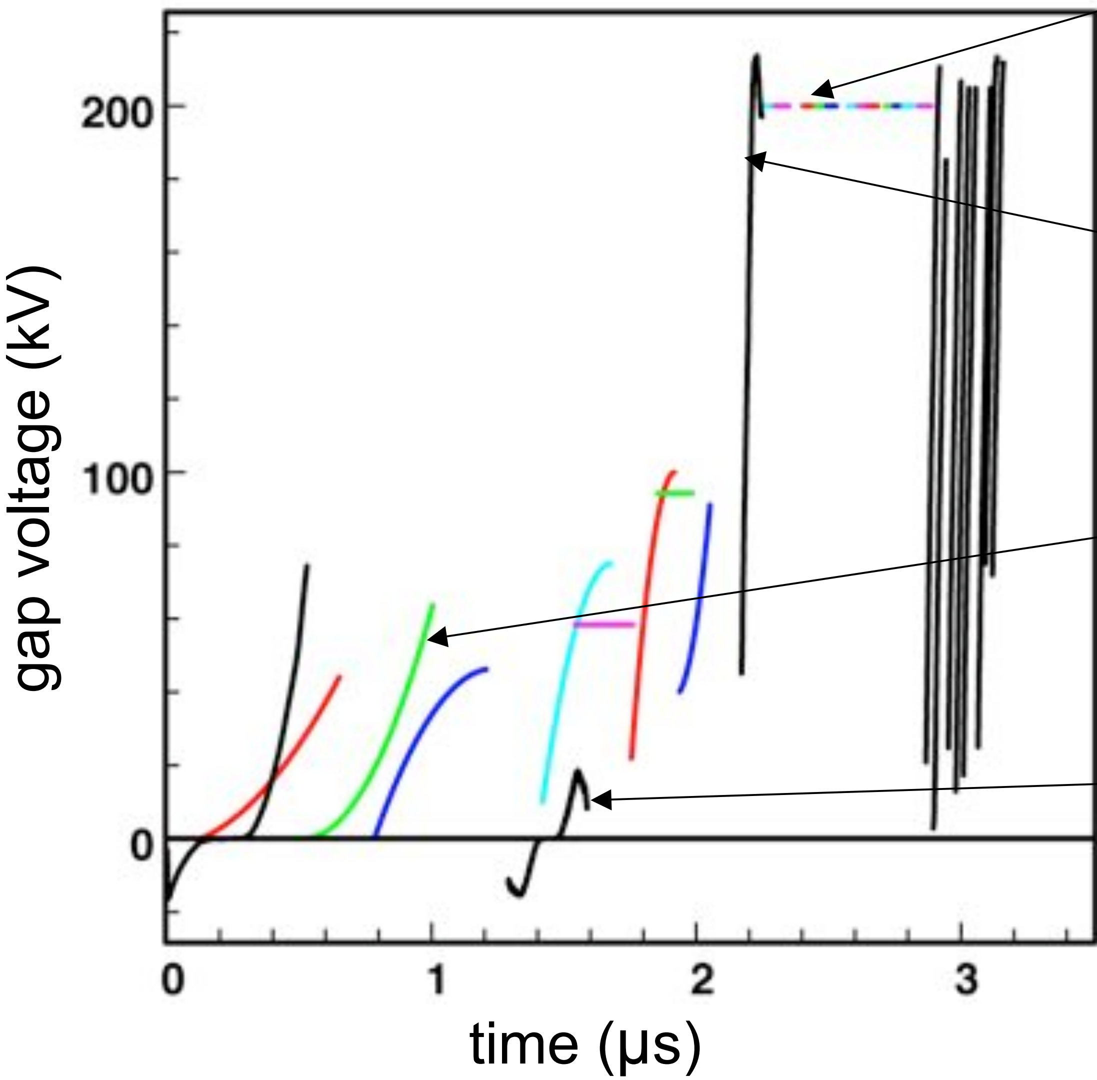
Pulse length vs z: the "bounce" is evident



Pulse duration vs z



Voltage waveforms for all gaps



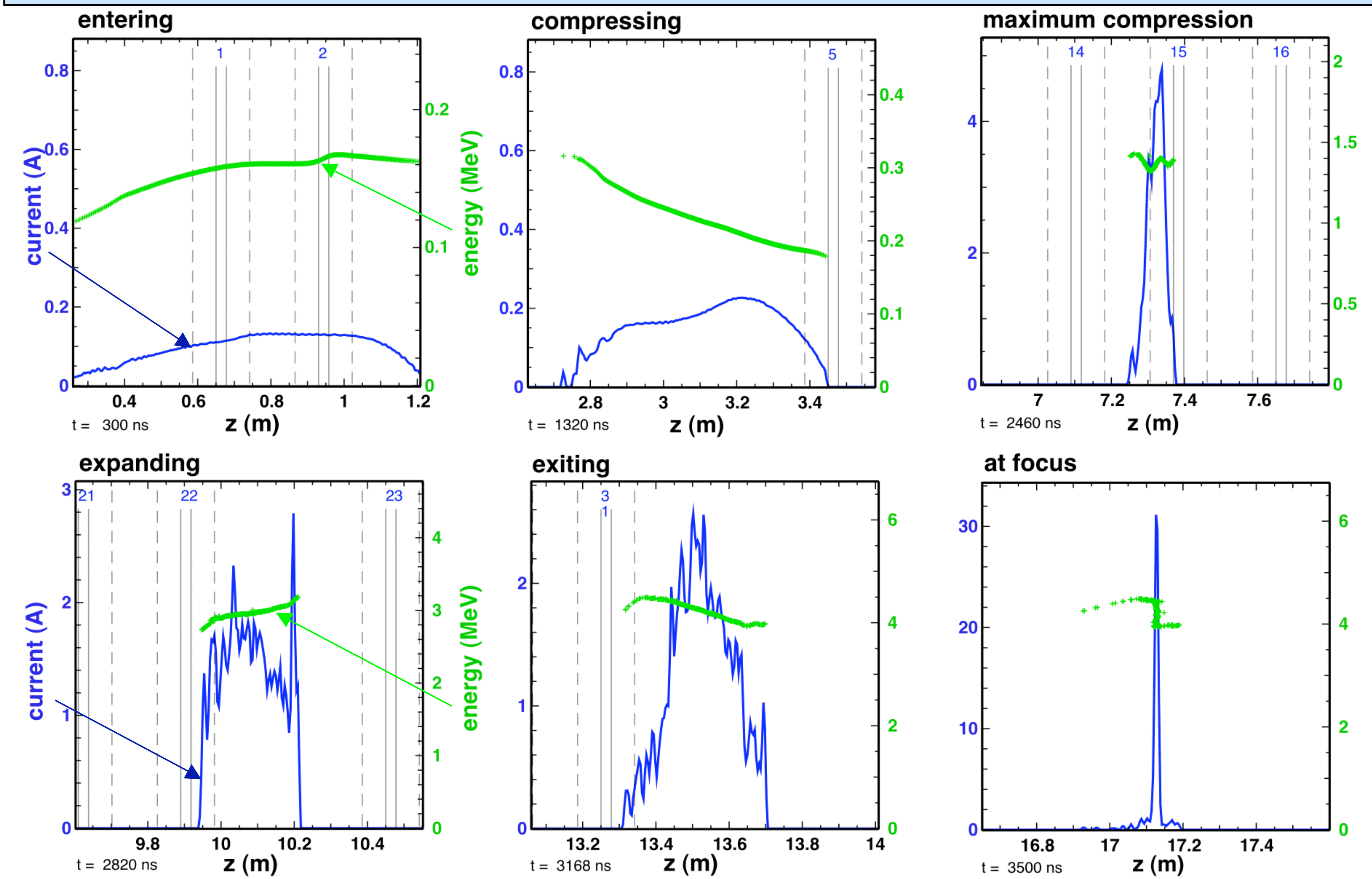
"flat-top" (here idealized)

"ramp" (here from an ATA cell)

"shaped" (to impose velocity tilt for initial compression)

"ear" (to confine beam ends)

A series of snapshots from ASP shows the evolution of the longitudinal phase space (kinetic energy vs z) and current



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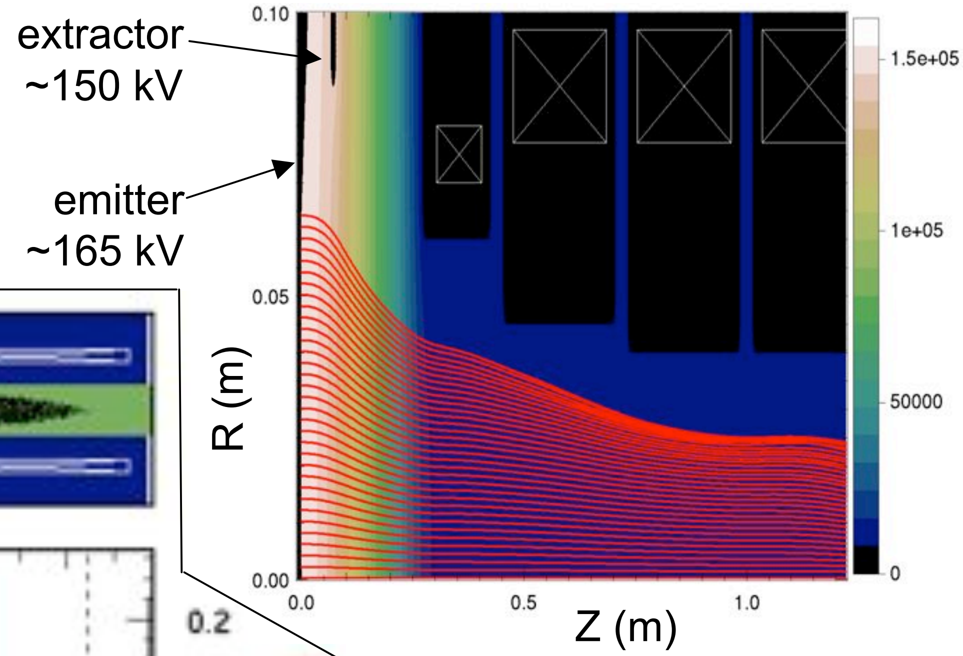
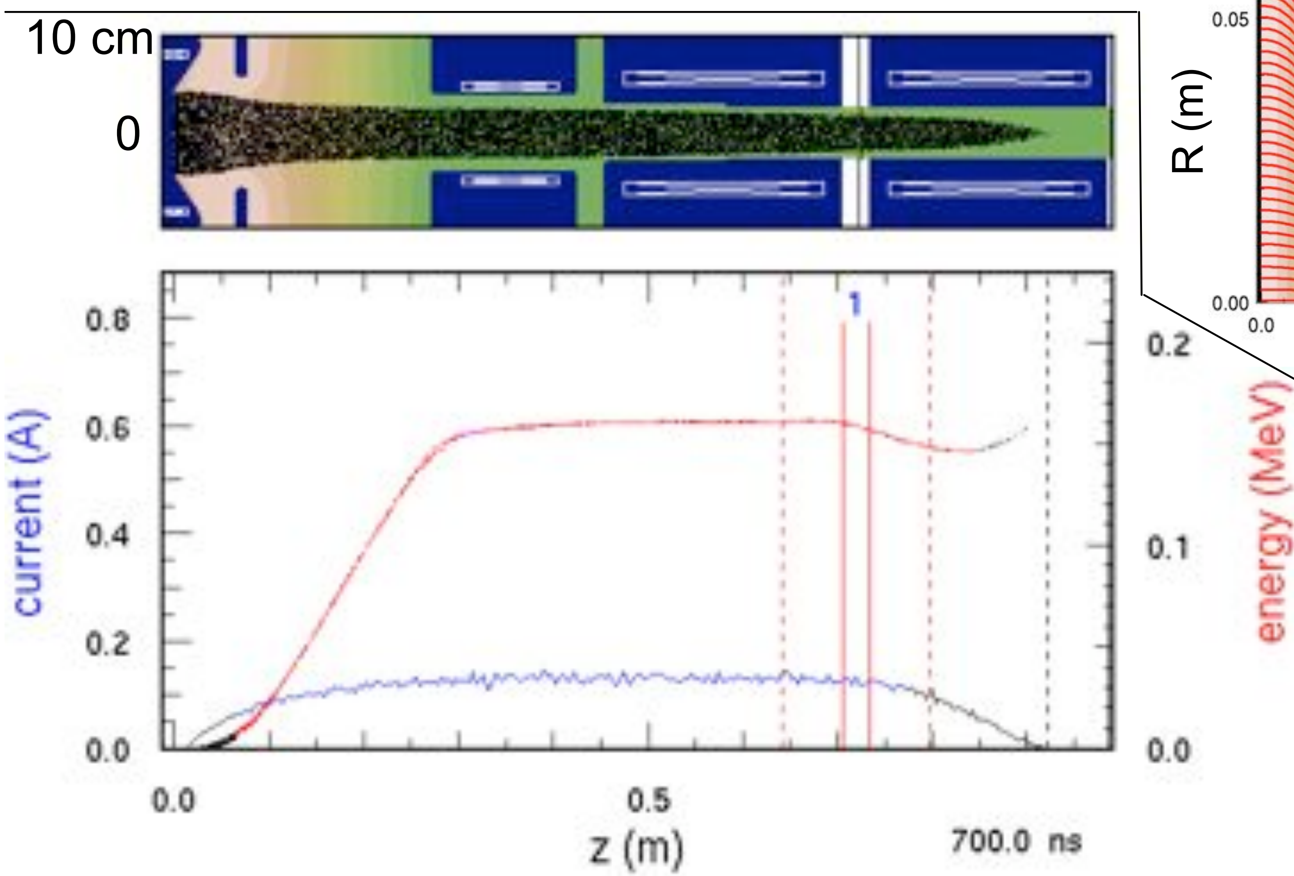
Design of injector for 1 mA/cm^2 Li^+ emission uses Warp in (r,z)

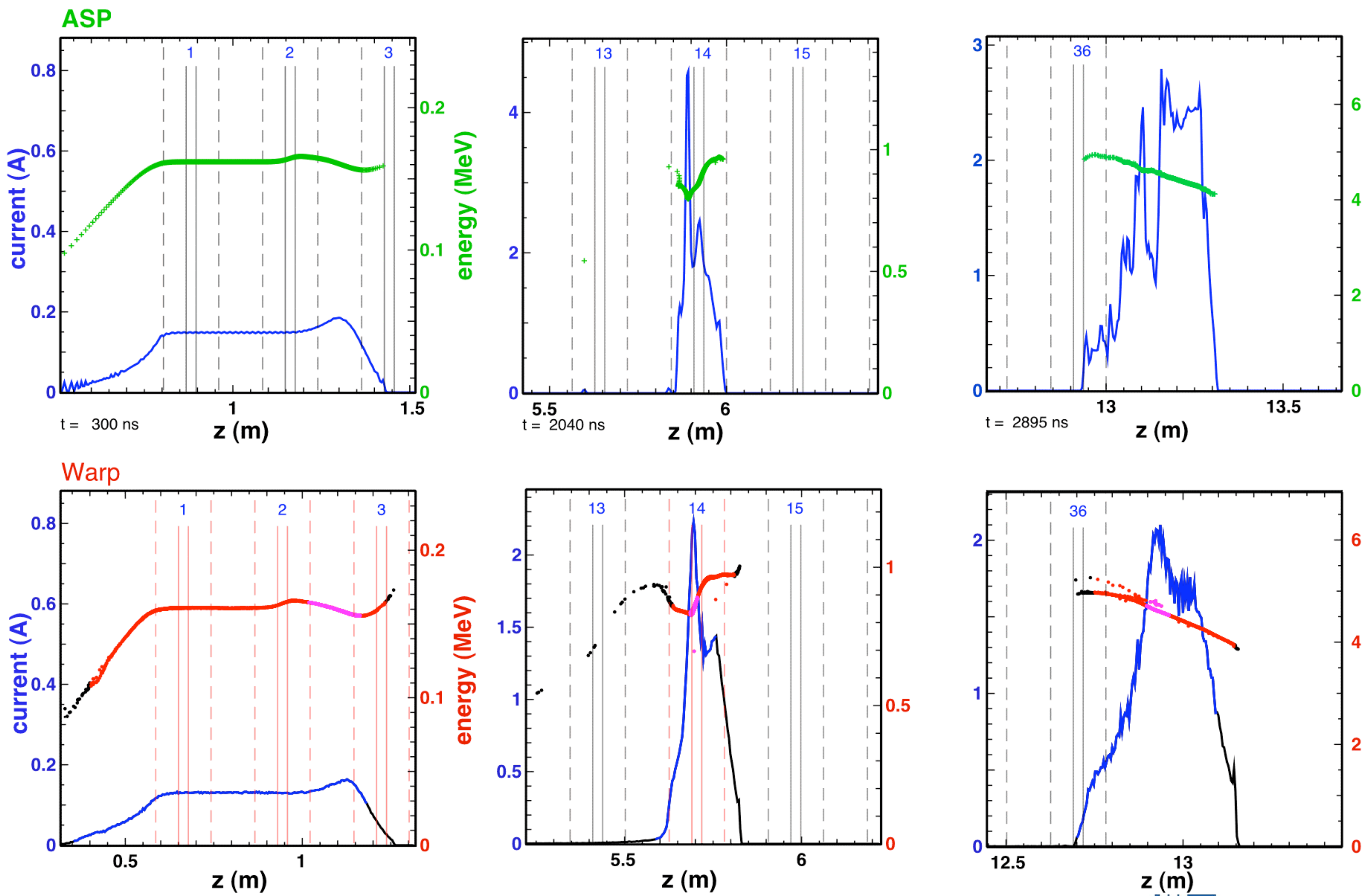
Using Warp's "gun" mode



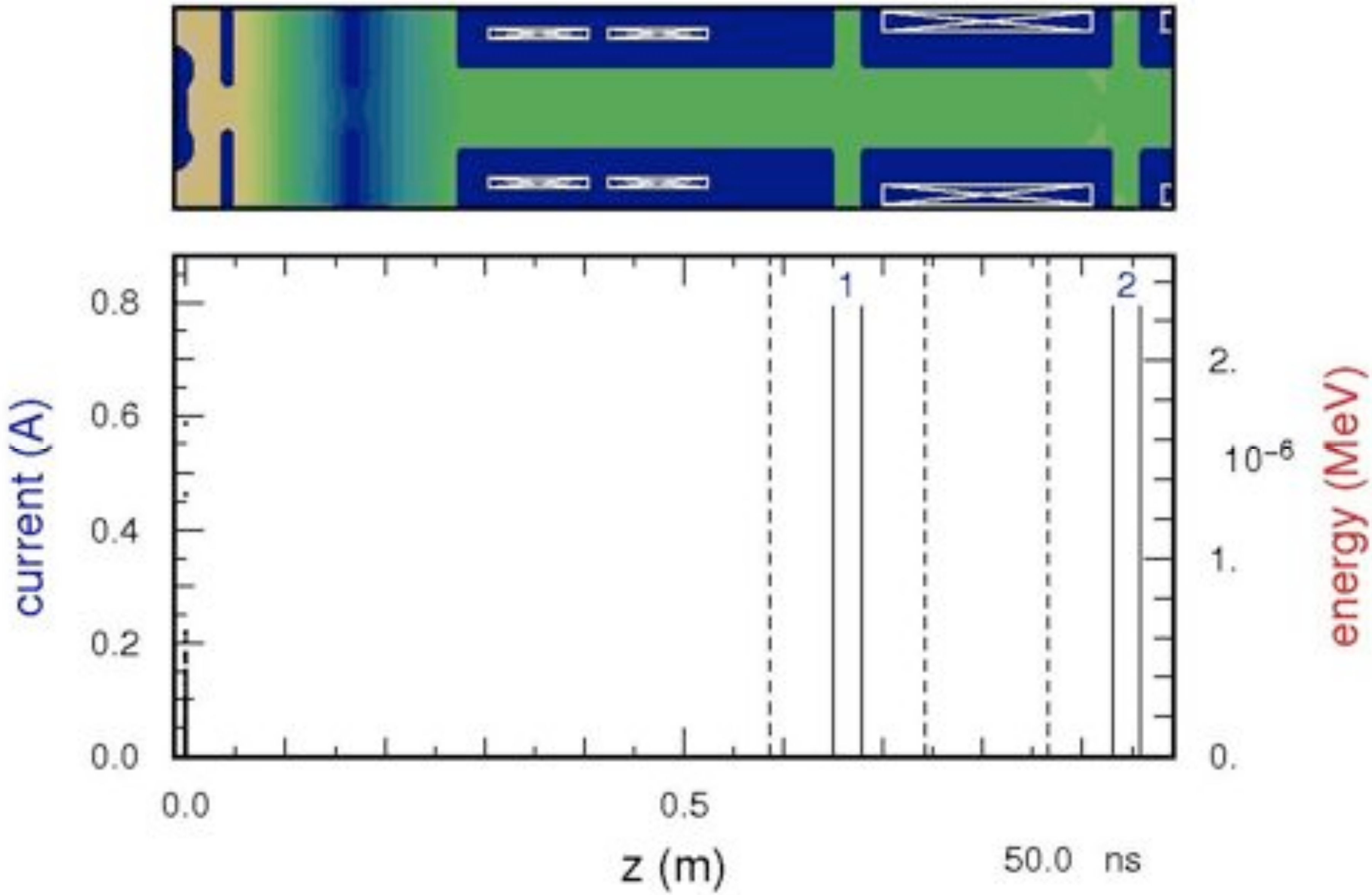


Using time-dependent space-charge-limited emission and simple mesh refinement

ASP & Warp results agree (when care is taken w/ initial beam)



Video: Warp (r,z) simulation of NDCX-II beam



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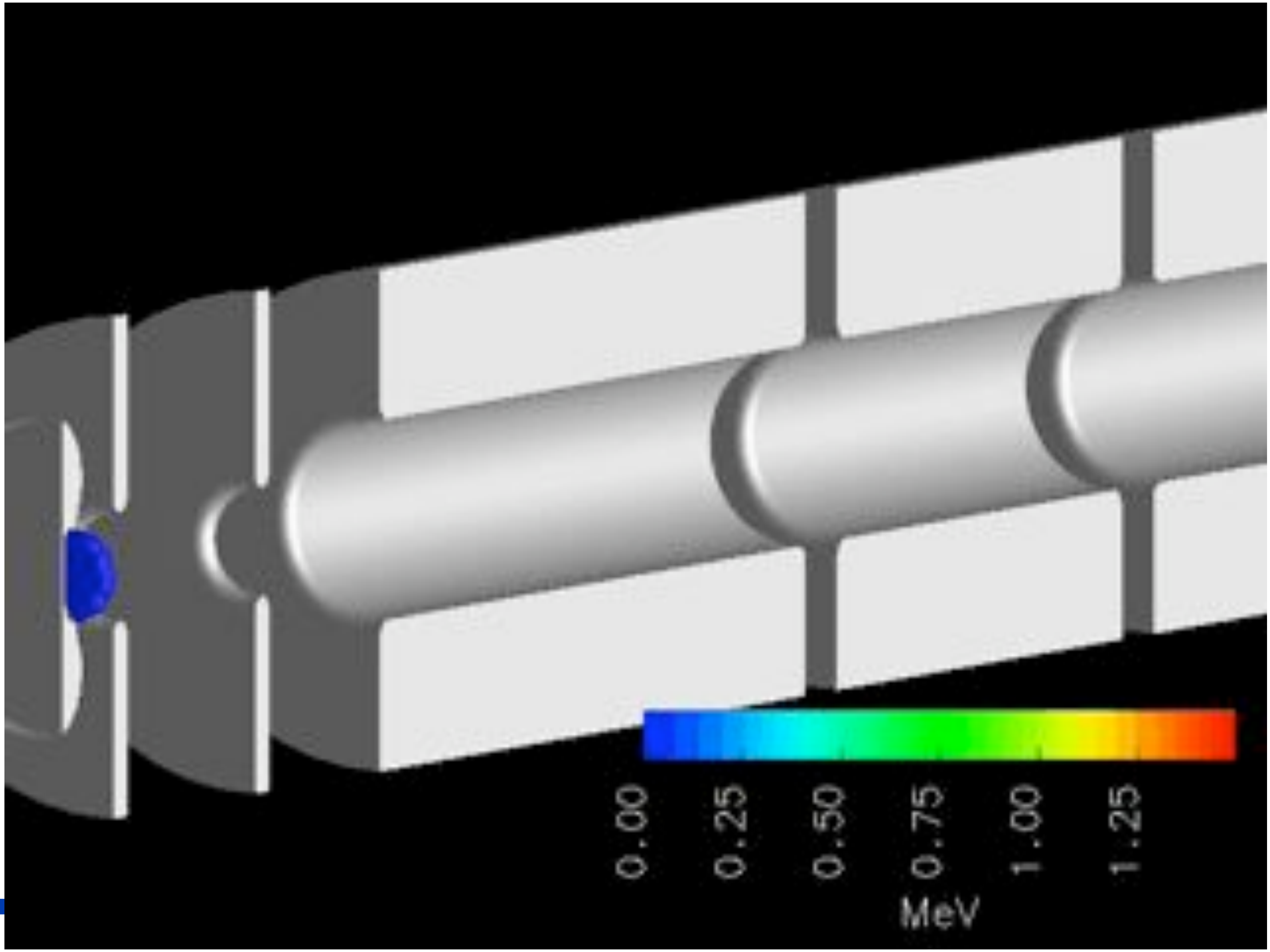
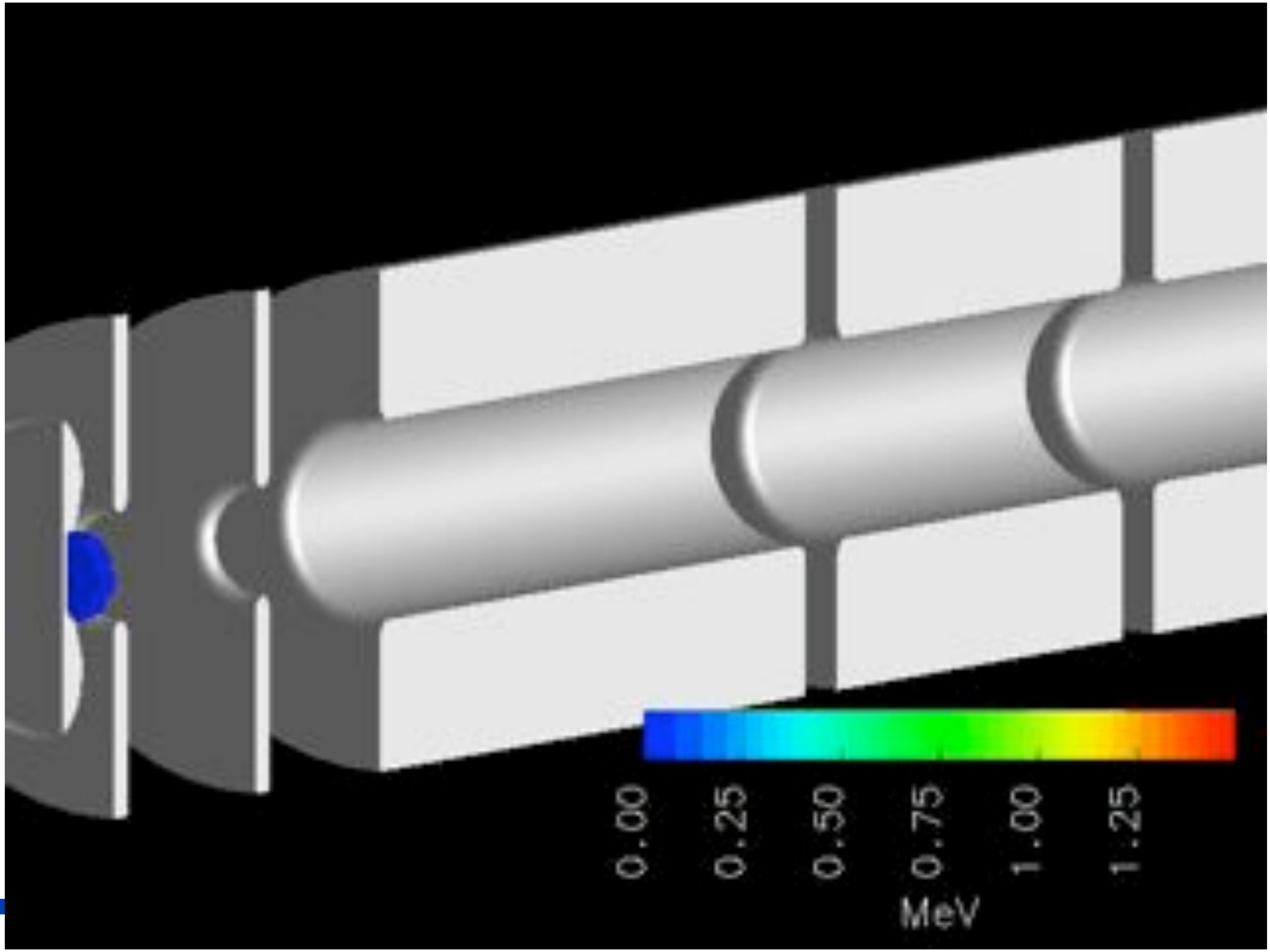
Video: Warp 3-D simulation of NDCX-II beam (no misalignments)

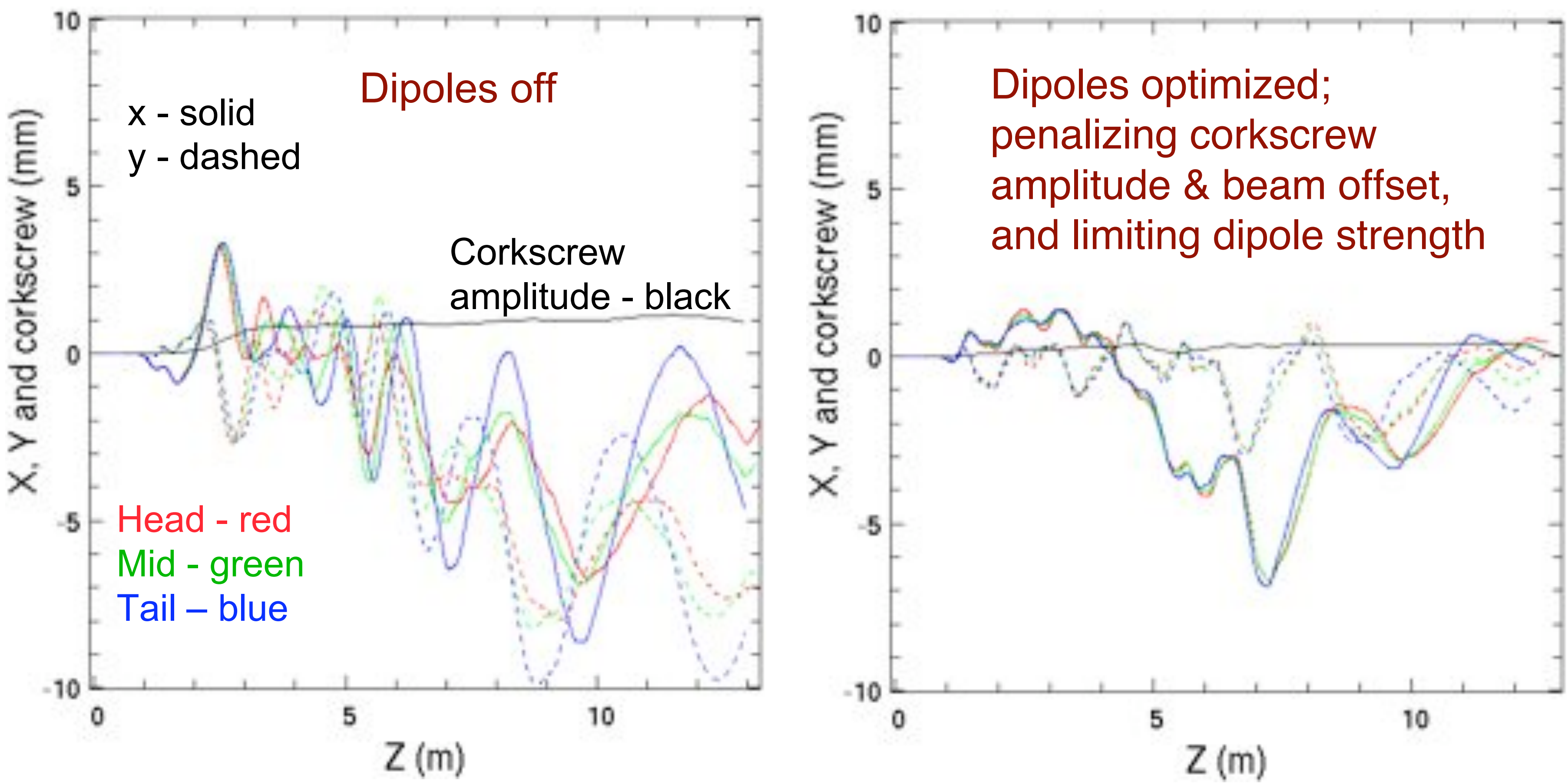


Video: Warp 3D simulation of NDCX-II, including random offsets of solenoid ends by up to 1 mm (0.5 mm is nominal)



ASP employs a tuning algorithm (as in ETA-II, DARHT)† to adjust "steering" dipoles so as to minimize a penalty function

Trajectories of head, mid, tail particles, and corkscrew amplitude, for a typical 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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Key technical issues are being addressed

- Li^+ ion source current density
  - We currently assume only 1 mA/cm^2
- Solenoid misalignment effects
  - Steering reduces corkscrew but requires beam position measurement
  - If capacitive or magnetic BPM's prove too noisy, we'll use scintillators or apertures
- Require "real" acceleration waveforms
  - A good "ramp" has been tested and folded into ASP runs
  - We're developing shaping circuits for "flatter flat-tops"
- Pulsed solenoid effects
  - Volt-seconds of ferrite cores are reduced by return flux of solenoids
  - Eddy currents (mainly in end plates) dissipate energy, induce noise
  - We'll use flux-channeling inserts and/or windings, & thinner end plates

We look forward to a novel and flexible research platform

- NDCX-II will be a unique ion-driven user facility for warm dense matter and IFE target physics studies.
- The machine will also allow beam dynamics experiments relevant to high-current fusion drivers.
- The baseline physics design makes efficient use of the ATA components through rapid beam compression and acceleration.