Toward a physics design for NDCX-II, a next-step platform for ion beam-driven physics studies*

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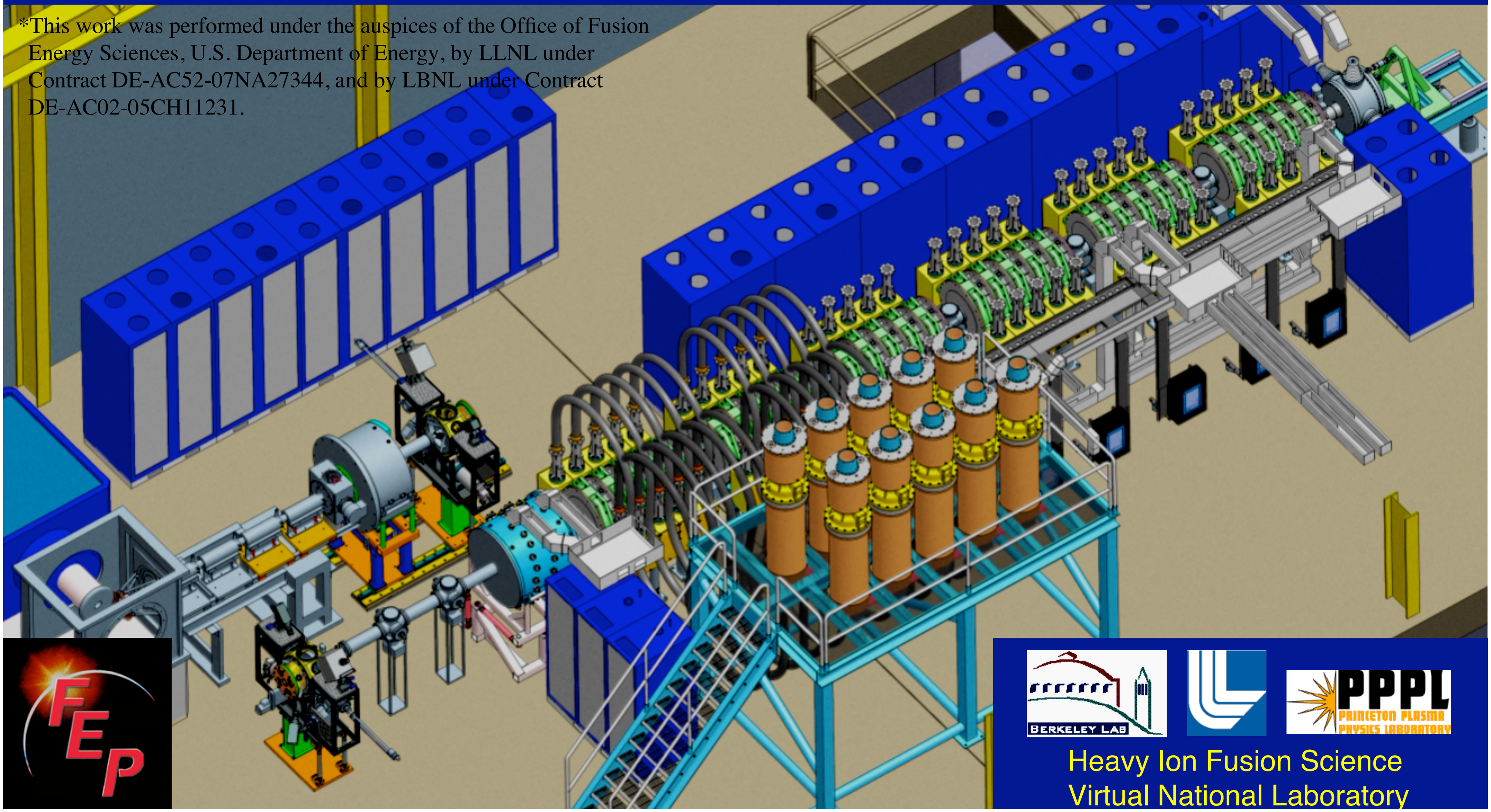

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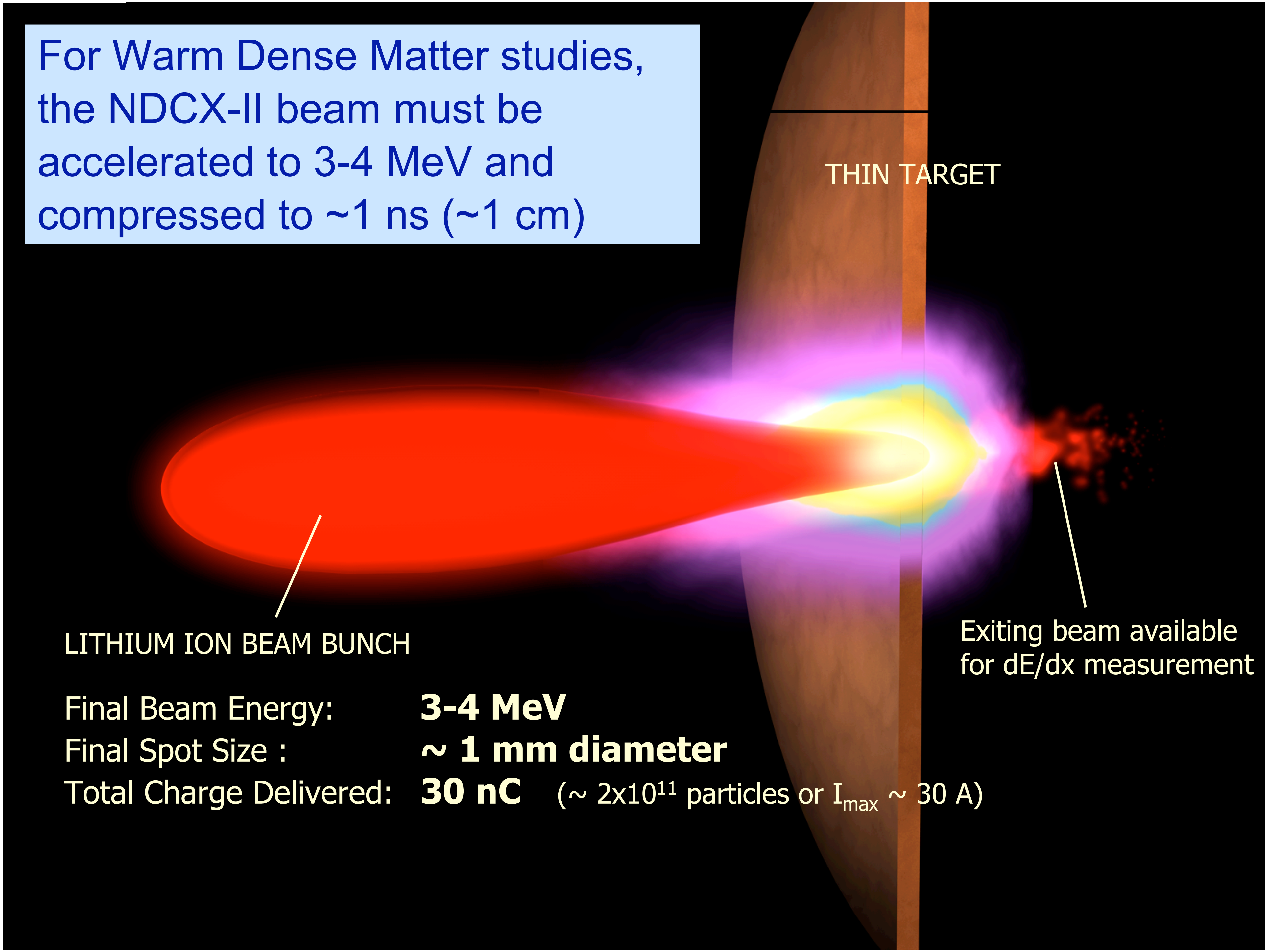
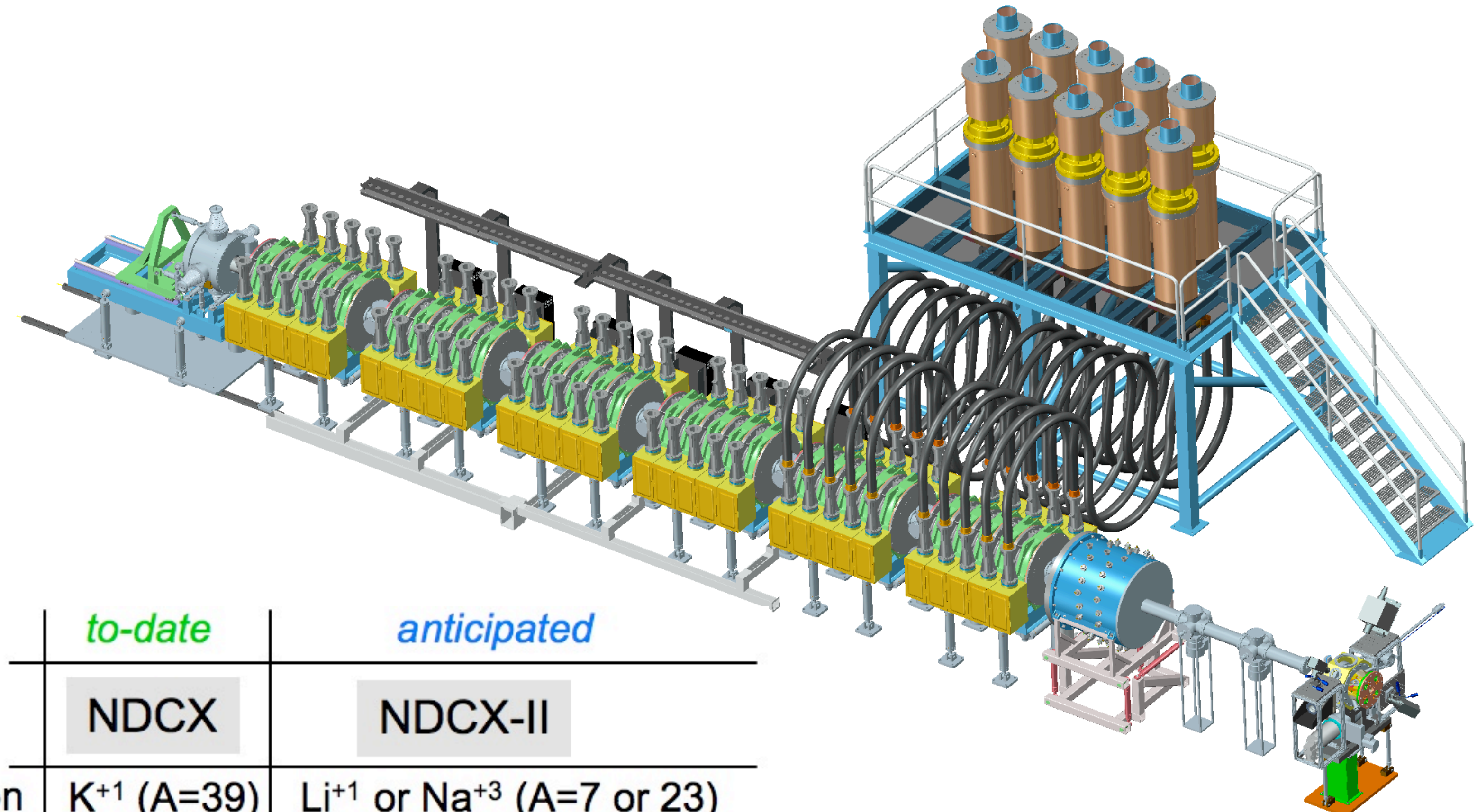
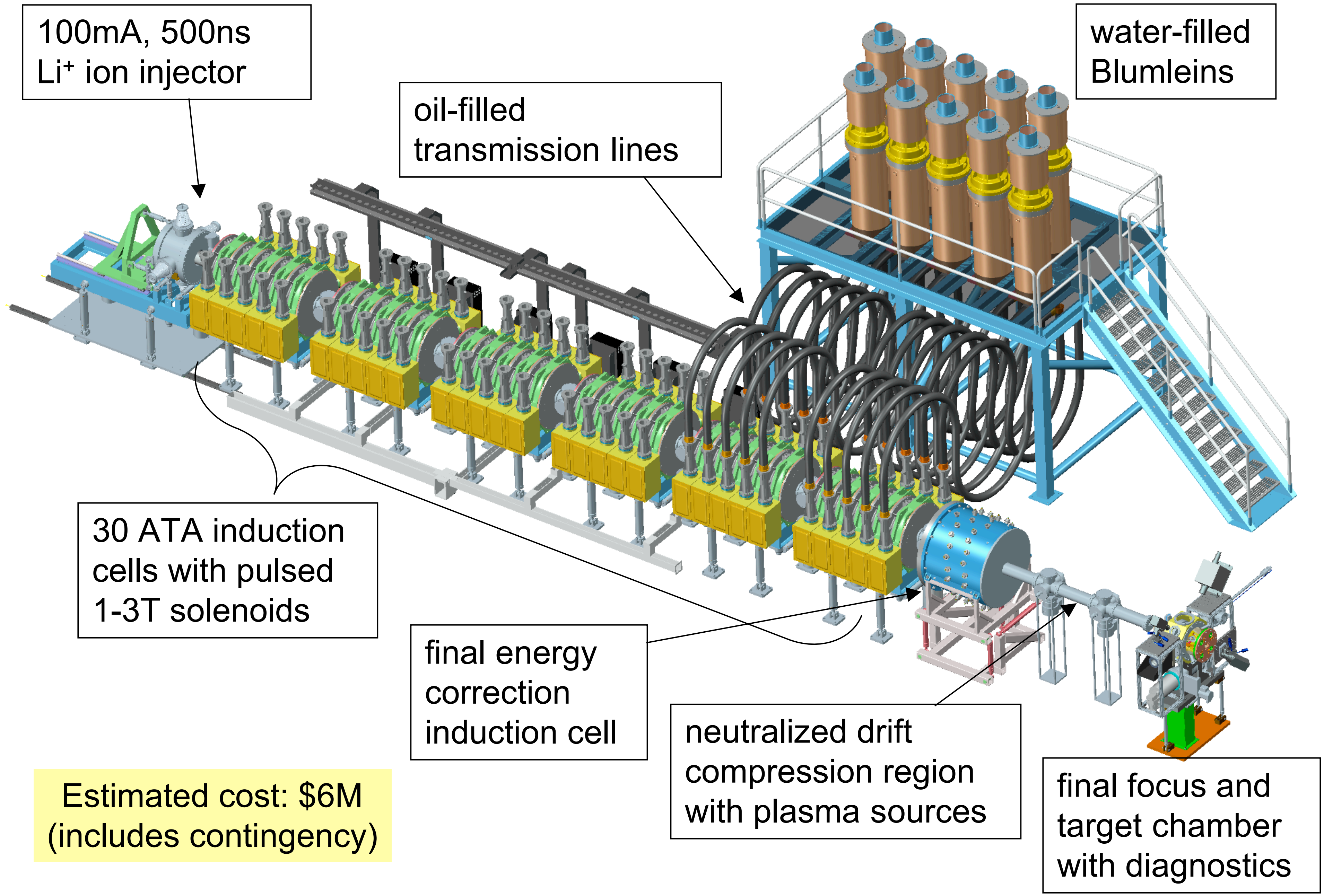

For Warm Dense Matter studies, the NDCX-II beam must be accelerated to 3-4 MeV and compressed to ~1 ns (~1 cm)
THIN TARGET
LITHIUM ION BEAM BUNCH
Exiting beam available for dE/dx measurement
Final Beam Energy: **3-4 MeV**
Final Spot Size : **~ 1 mm diameter**
Total Charge Delivered: **30 nC** (~ $2x10^{11}$ particles or I_{max} ~ 30 A)

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



	to-date	*anticipated*
	NDCX	NDCX-II
Ion	K^{+1} (A=39)	Li^{+1} or Na^{+3} (A=7 or 23)
Ion energy	400 keV	3 - 16 MeV
Focal radius	1.5 - 3 mm	0.5 mm
Pulse duration	2 - 4 ns	1 ns
Compression ratio	60X	500X
Peak current	~ 2 A	~ 30 A

At least 40 ATA cells are available for NDCX-II



Estimated cost: $6M
(includes contingency)

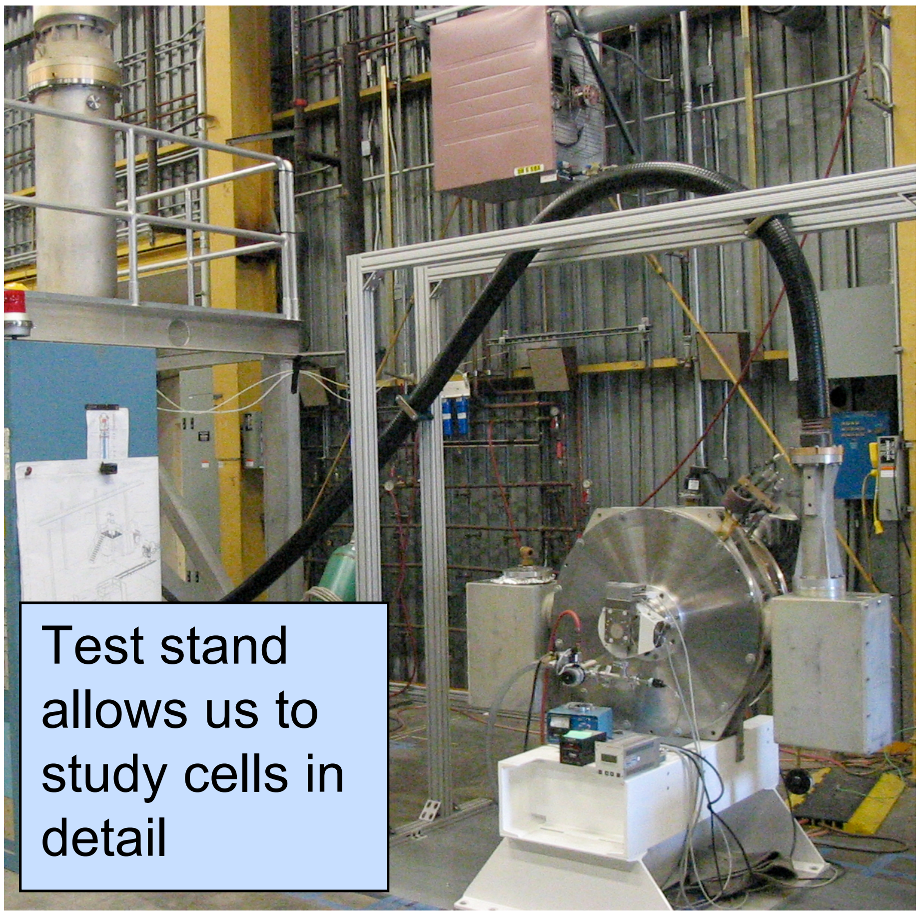
NDCX-II represents a significant upgrade over NDCX-I

	Ion (atomic number / mass of common isotope)	Linac voltage - MV	Ion energy - MeV	Beam energy - J	Target pulse - ns	Range -microns (in ..)	Energy density $10^{11} J/m^3$
NDCX-I	K^+ (19 / 39)	0.35	0.35	0.001-0.003	2-3	0.3/1.5 (in solid/ 20% Al)	0.04 to 0.06
NDCX-II	Li^{+1} (3 / 7) or Na^{+3} (11 / 23)	3.5 - 5	3.5 - 15	0.1 - 0.28	1-2 (or 5 w hydro)	7 - 4 (in solid Al)	0.25 to 1

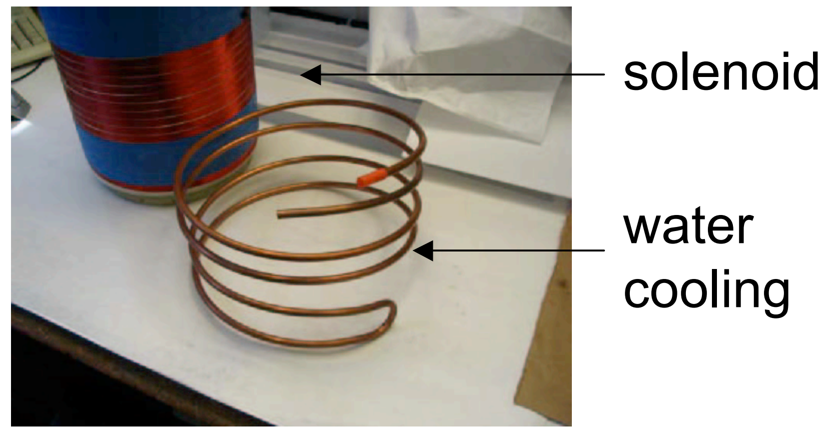
- Baseline for WDM experiments: 1-ns Li^+ pulse (~ $2x10^{11}$ ions, 30 nC, 30 A)
- For experiments relevant to ion direct drive: require a longer pulse with a "ramped" kinetic energy, or a double pulse.

ATA cells are in good condition and match NDCX-II needs well

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

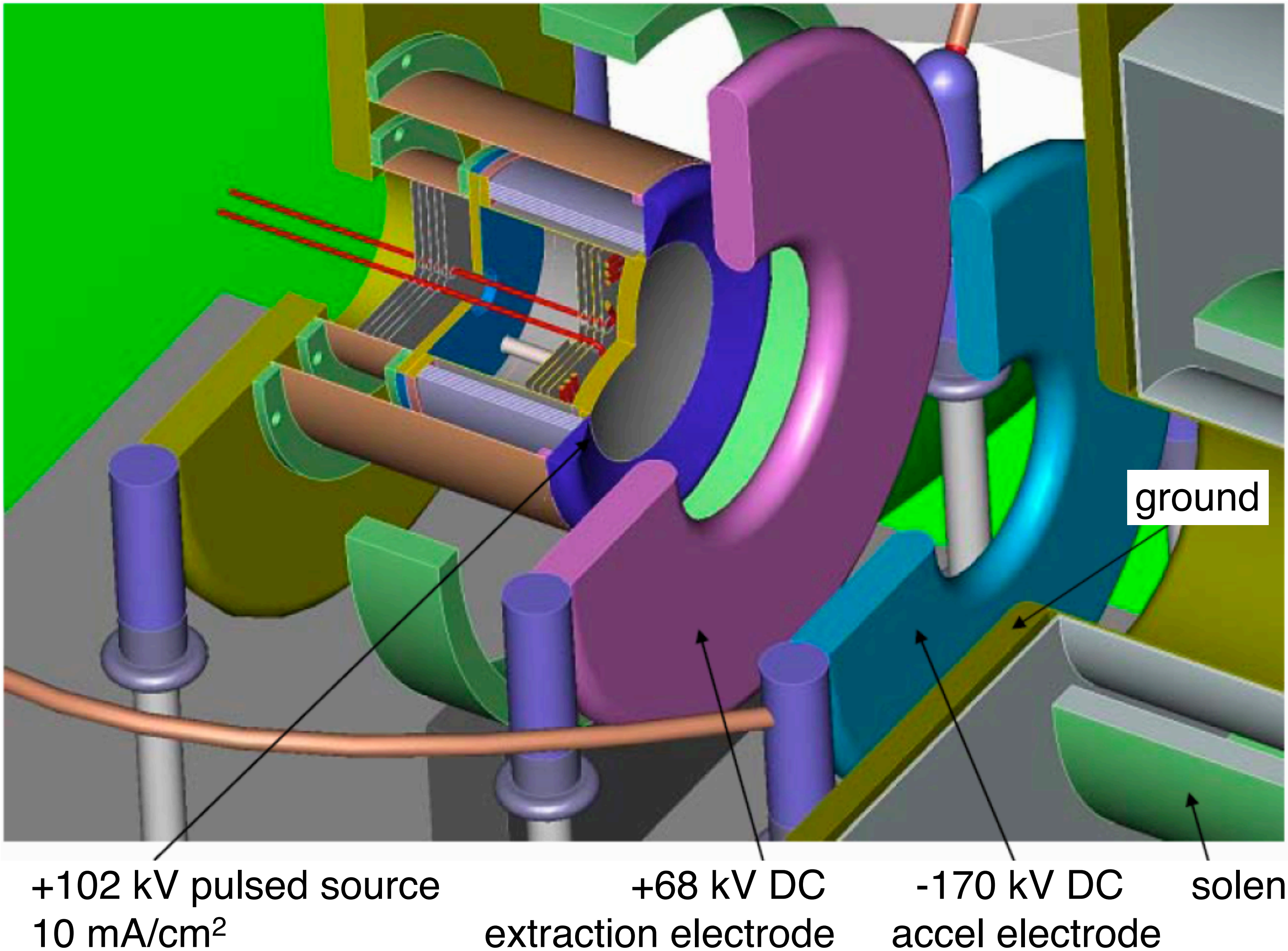


Test stand allows us to study cells in detail



Cells will be refurbished with stronger, pulsed solenoids

NDCX-II uses an accel-decel injector in which the "einzel lens" effect provides transverse confinement



Some issues were resolved; favorable features emerged

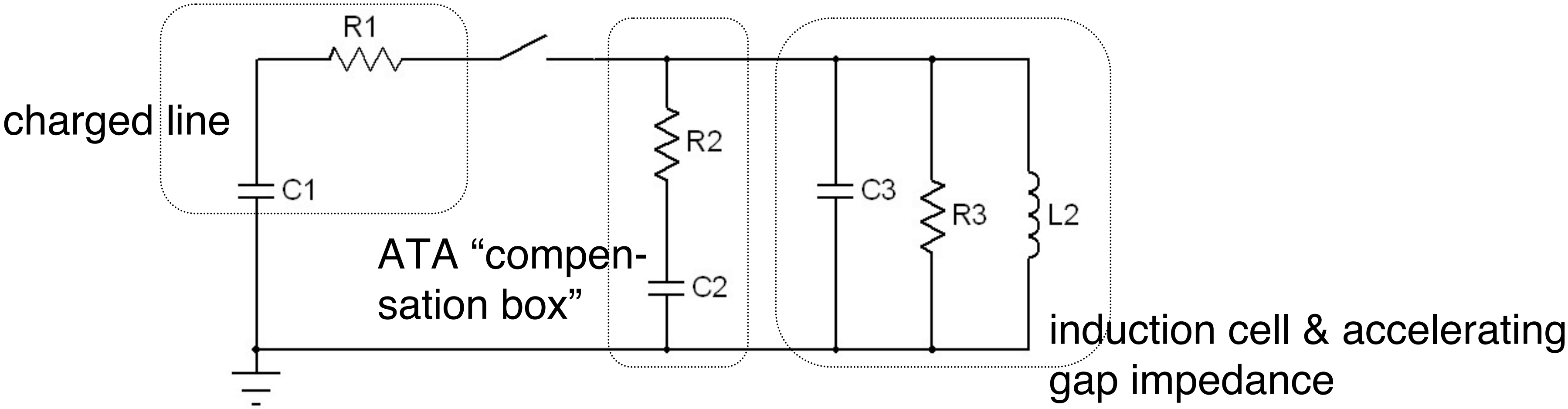
Issues:

- An accelerating gap must be "on" while any of the beam overlaps its extended fringe field
  - To shorten the fringe, the 6.7-cm radius of the ATA beam pipe is reduced to 4.0 cm
- Some pulses must be "shaped" to combat space charge forces
  - We'll do this via inexpensive passive circuits
- Space is limited
  - 30-cell design (20 Blumleins + 10 lower-voltage sources) fits easily

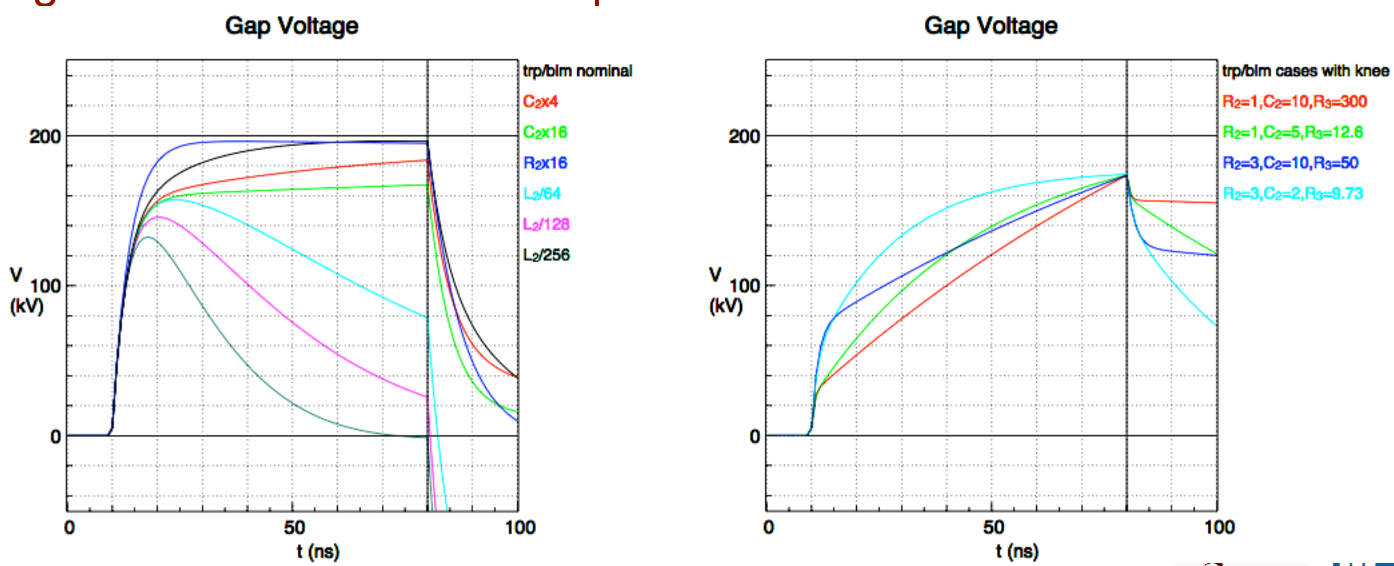
Favorable features:

- Most of machine uses modular 5-cell "blocks"
- Induction cells can impart all or most of final ~8% velocity "tilt"
- Current of compressed beam varies weakly w/ target plane over ~40 cm

A simple passive circuit can generate a wide variety of waveforms



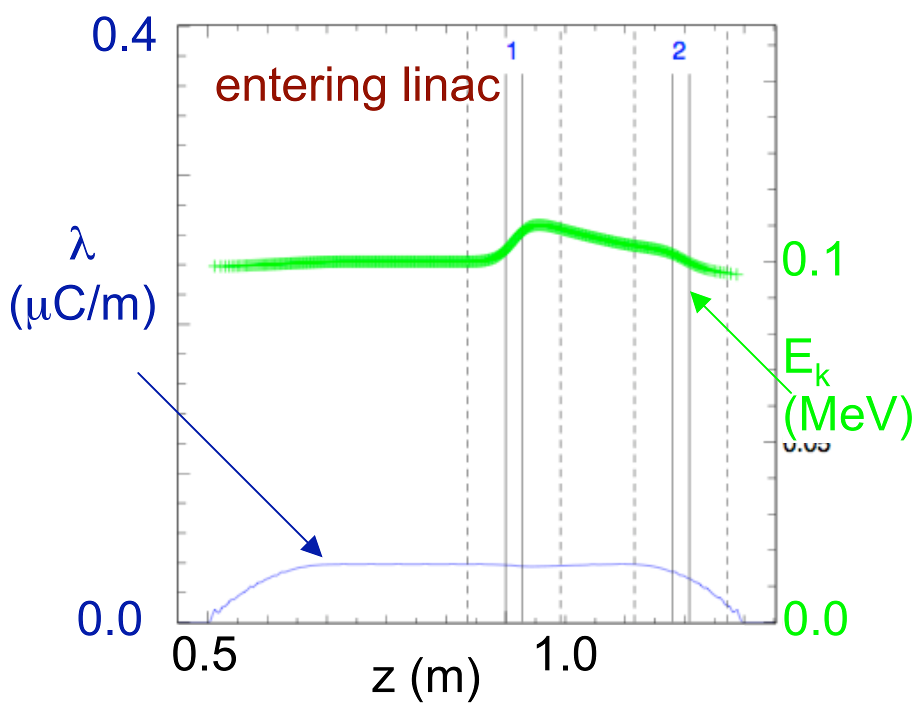
Waveforms generated for various component values:

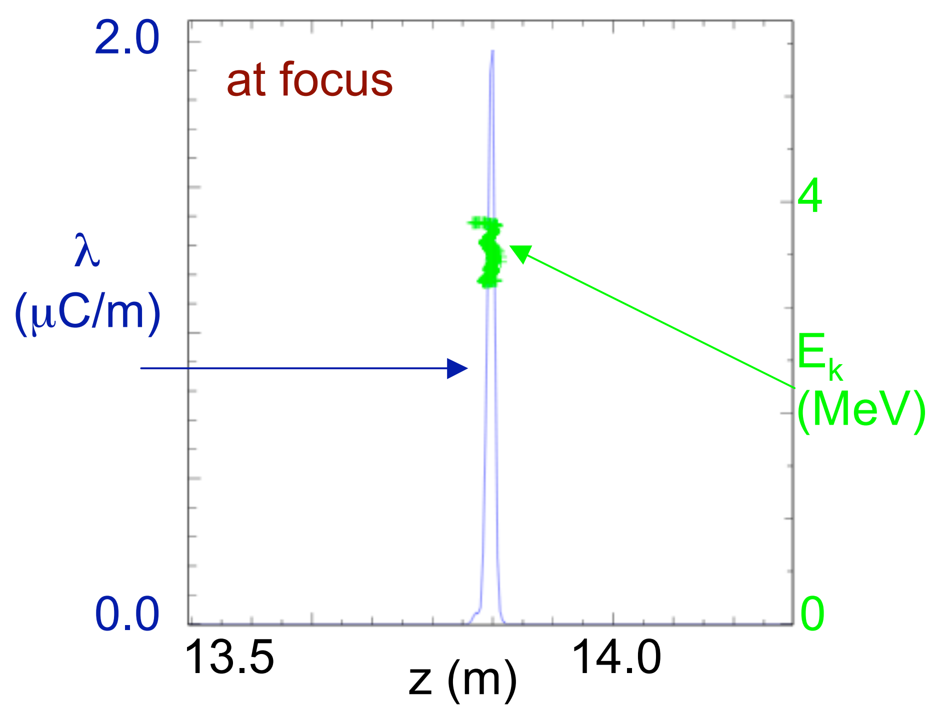


We are well on our way toward a physics design for NDCX-II

- Accel-decel injector produces a ~ 100 keV Li^+ beam with ~ 67 mA flat-top
- Induction accelerates it to 3.5 MeV at 2 A
- The 500 ns beam is compressed to ~ 1 ns in just ~ 14 m

From 1-D code:





Physics design effort relies on PIC codes

- 1-D PIC code that follows (z,v_z)
  - Poisson equation with transverse falloff ("HINJ model") for space charge

$$g_0 = 2 \log (r_{pipe} / r_{beam0}) \qquad k_\perp^2 = 4 / (g_0 r_{beam0}^2)$$

  - A few hundred particles
  - Models gaps as extended fringing field (Ed Lee's expression)
  - Flat-top initial beam with parabolic ends, with parameters from a Warp run
  - "Realistic" waveforms: flat-top,"triangles" from circuit equation, and low-voltage shaped "ears" at front end
  - Interactive (Python language)
- Warp
  - 3-D and axisymmetric (r,z) models; (r,z) used so far
  - Electrostatic space charge and accelerating gap fields
  - Time-dependent space-charge-limited emission

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

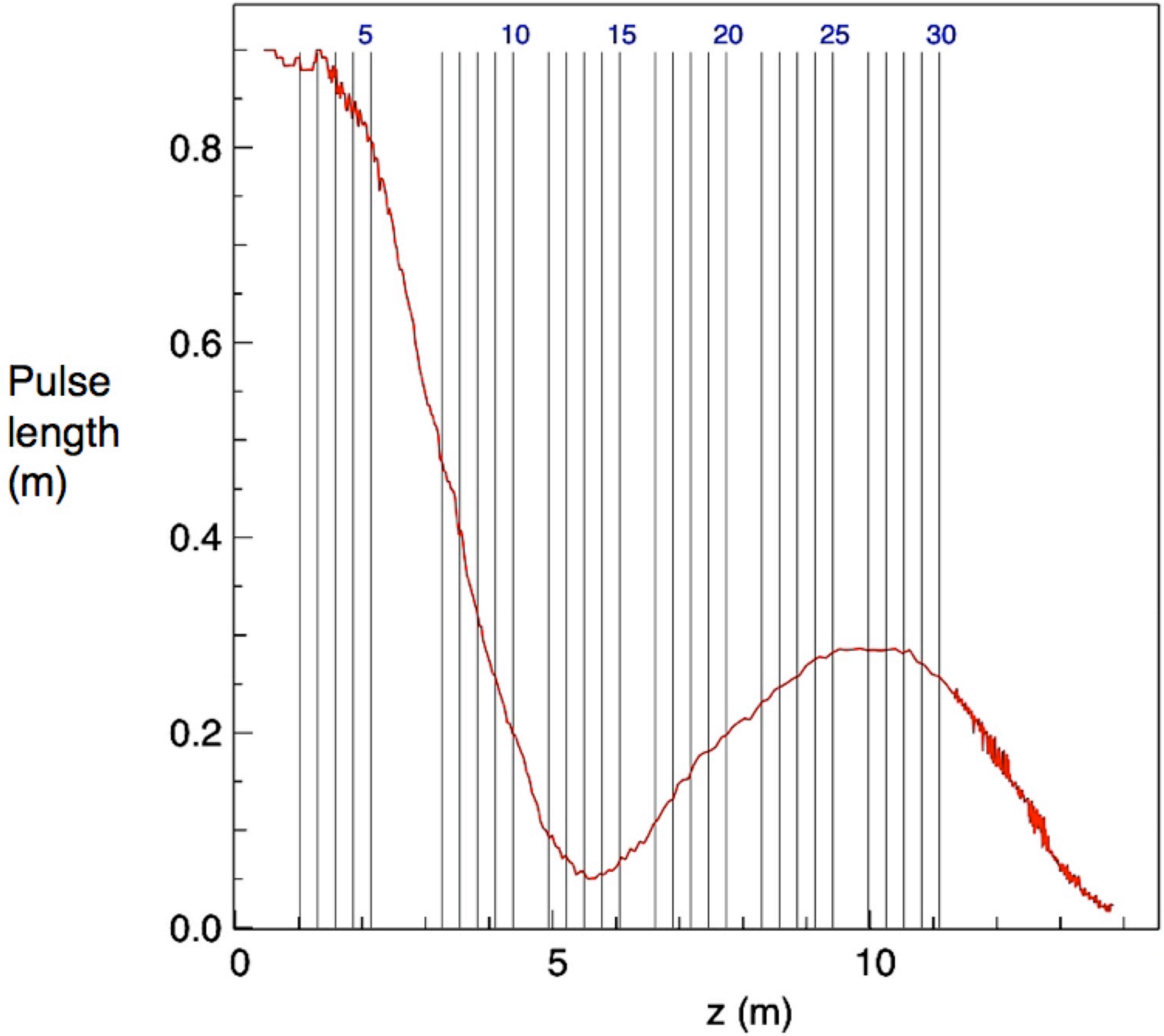
- Compress longitudinally before main acceleration
- Want < 70 ns transit time through gap (with fringe field) as soon as possible

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

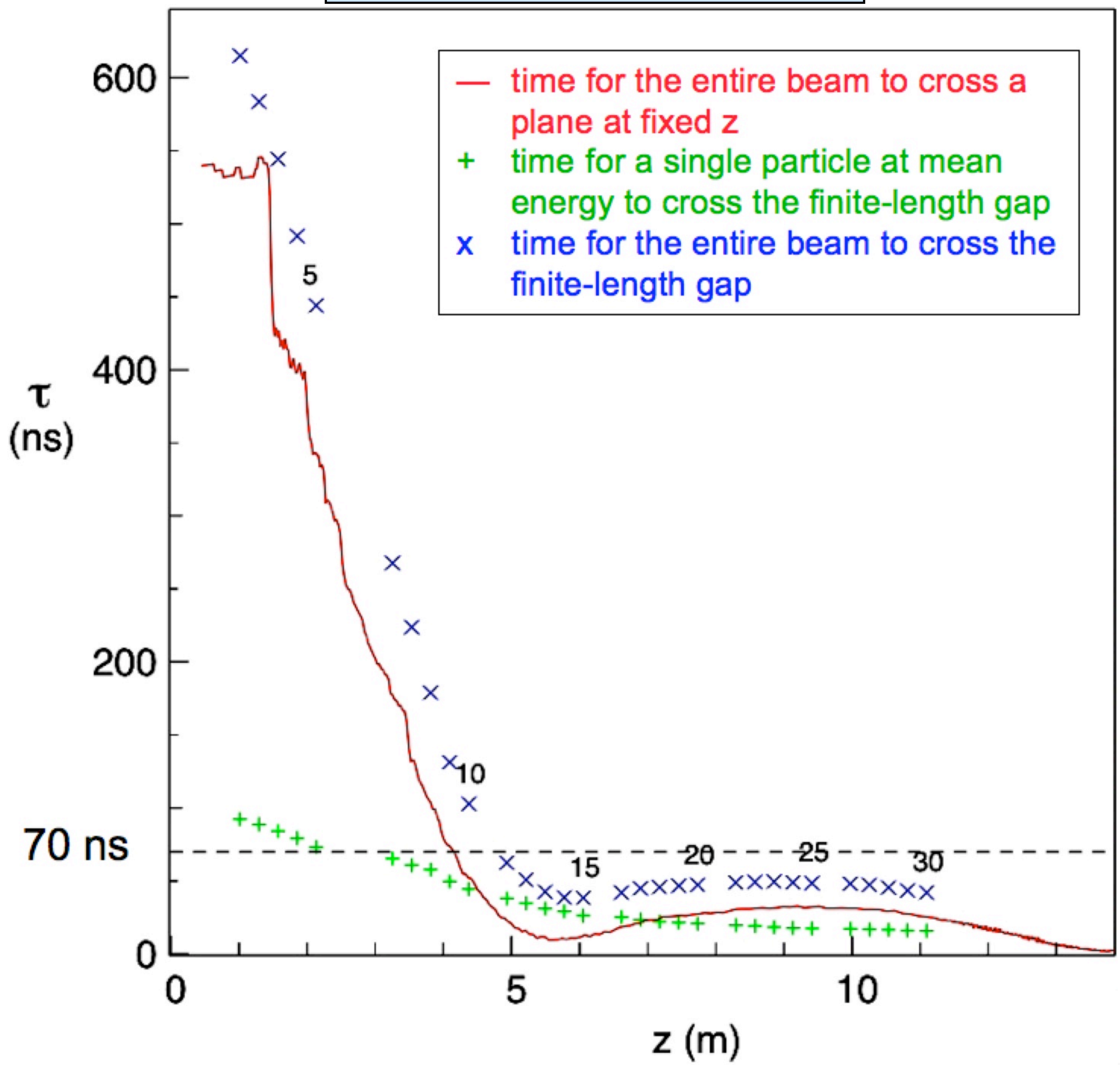
Principle 2: Let It Bounce

- 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

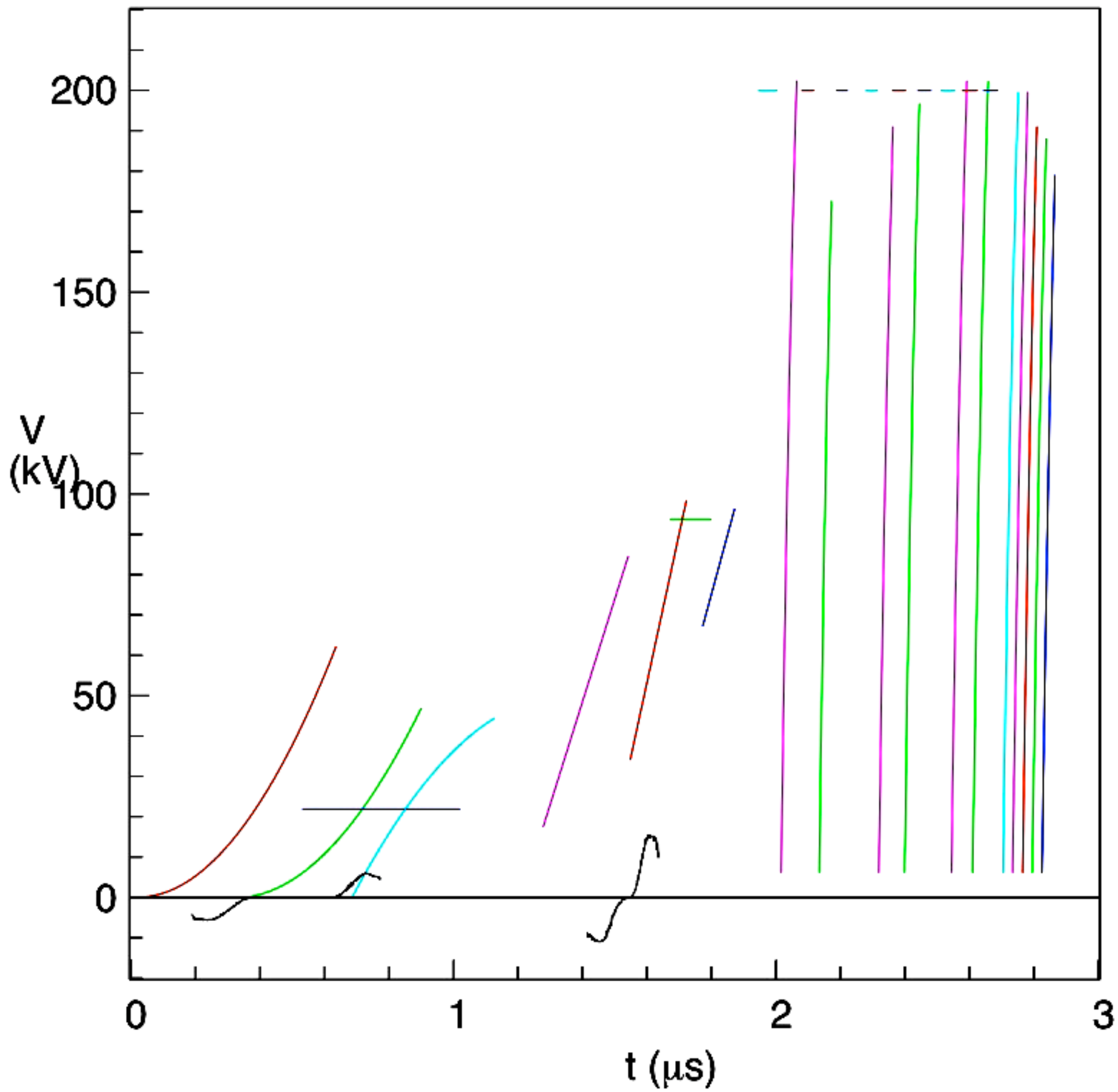
Pulse length (m) vs. z of center-of-mass



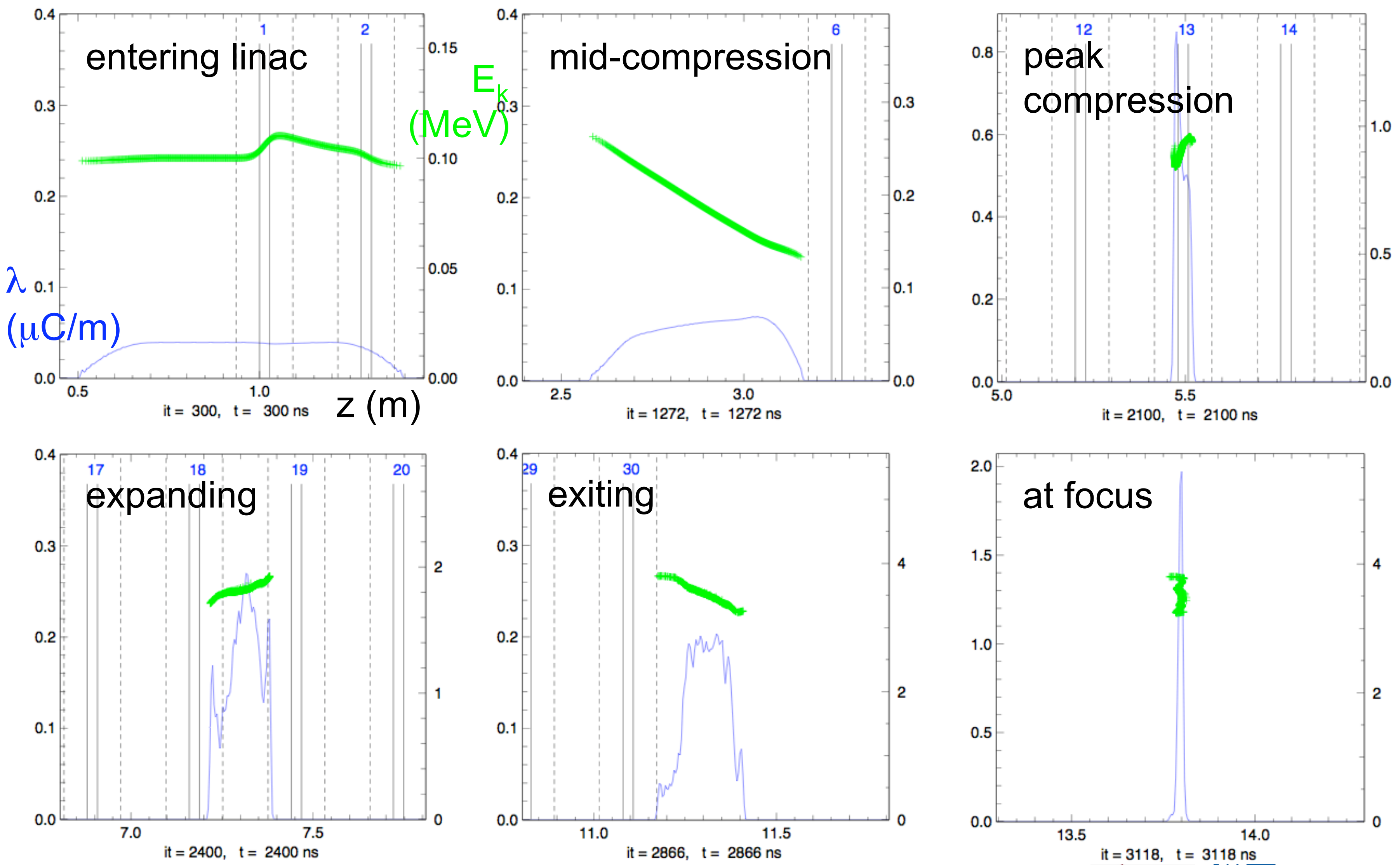
Pulse duration vs. z



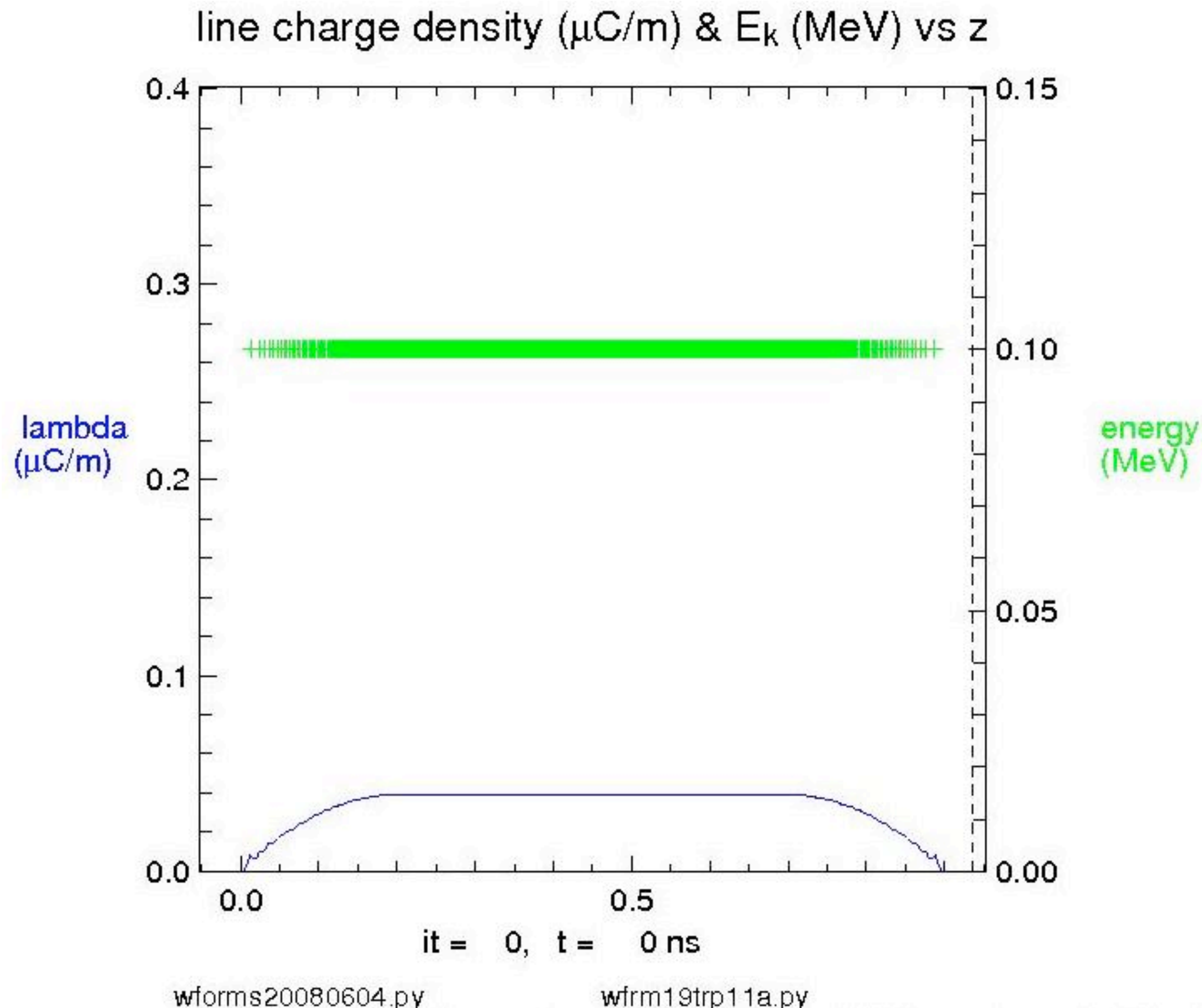
Voltage waveforms for all gaps



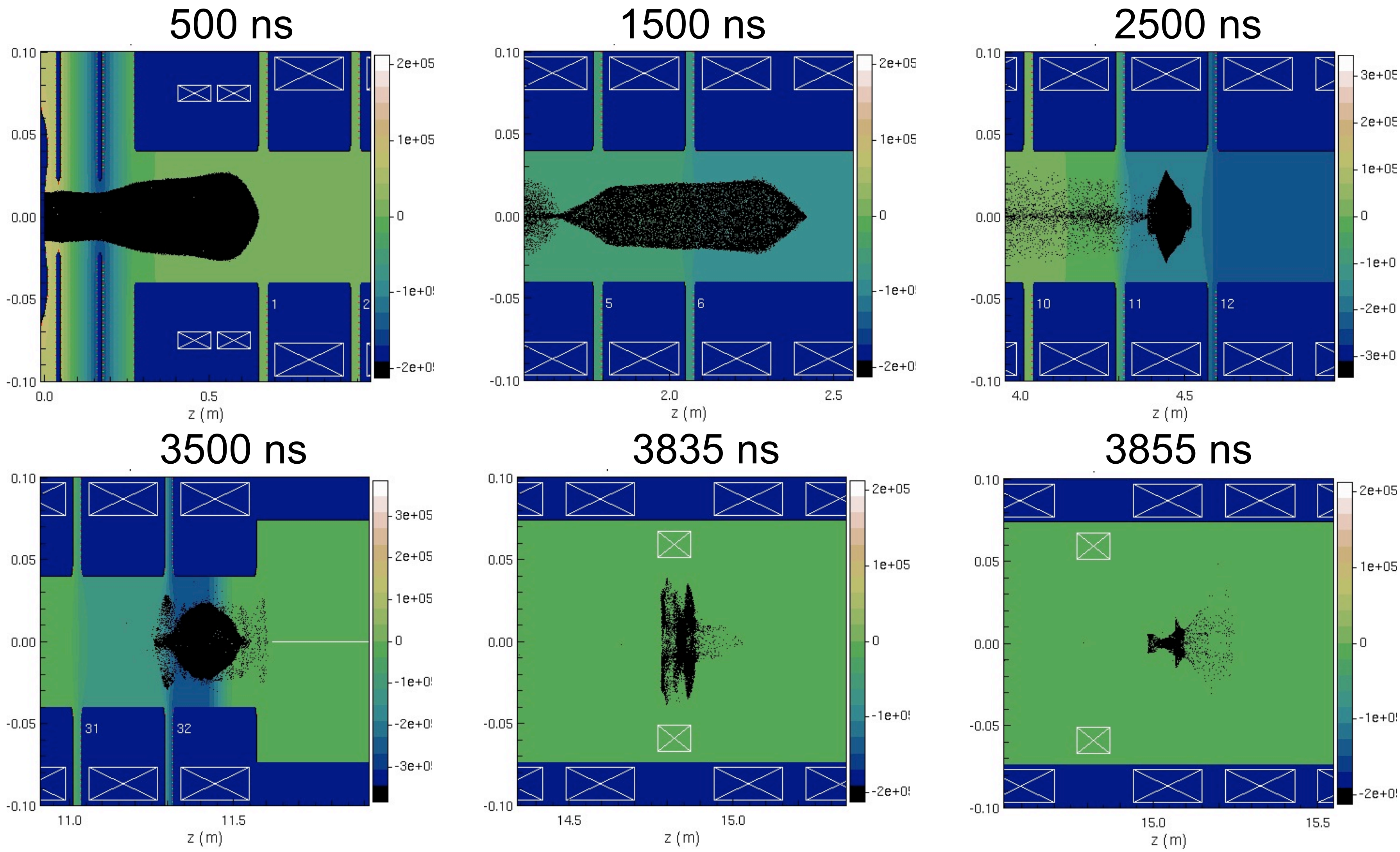
A series of snapshots shows how the (E_k,z) phase space and the line charge density evolve



Video: line charge density and kinetic energy profiles vs. time



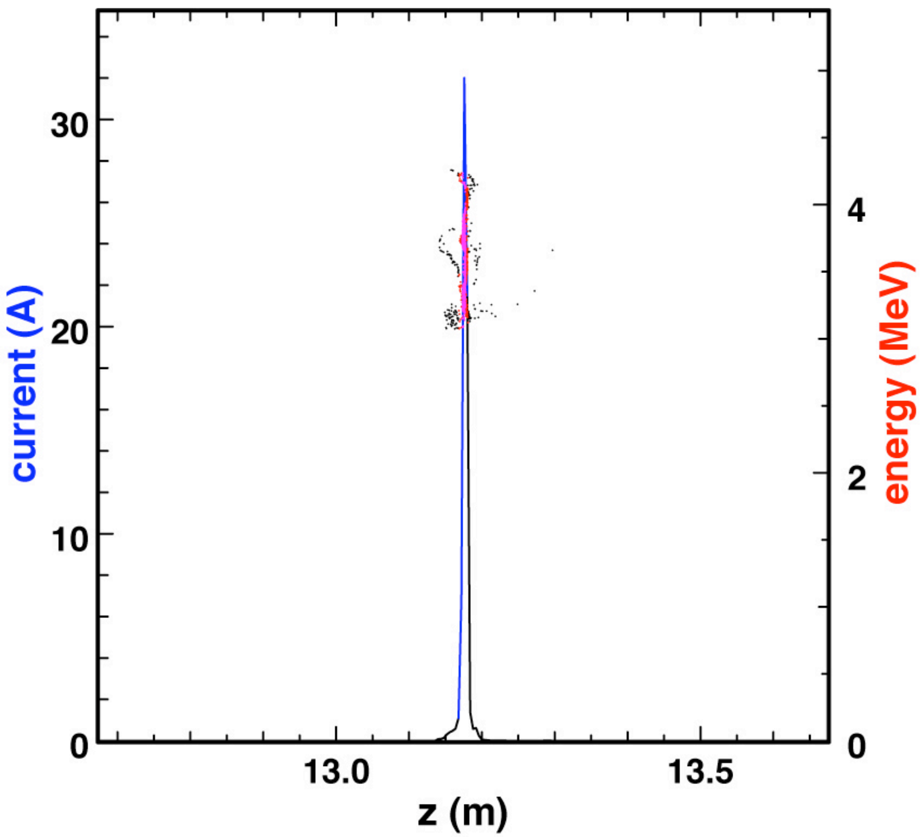
We use the Warp code to simulate the NDCX-II beam in (r,z)



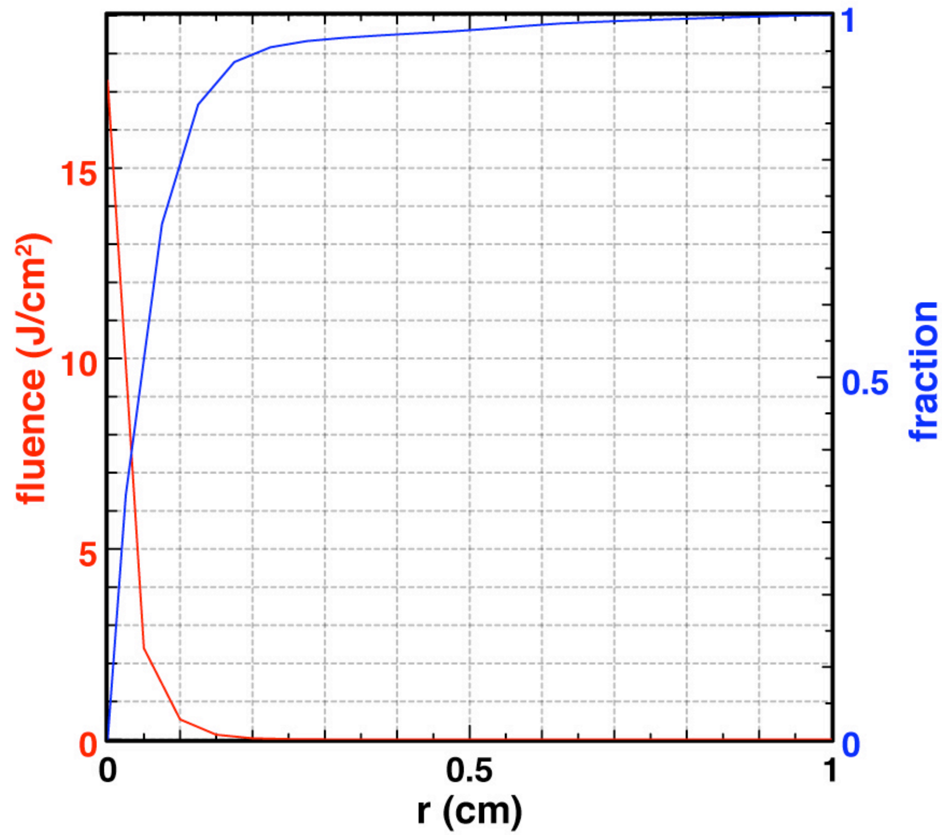
Transverse emittance growth (phase space dilution) is minimal

Preliminary Warp (r,z) beam-on-target is encouraging; transverse dynamics and focusing optics design is still at an early stage

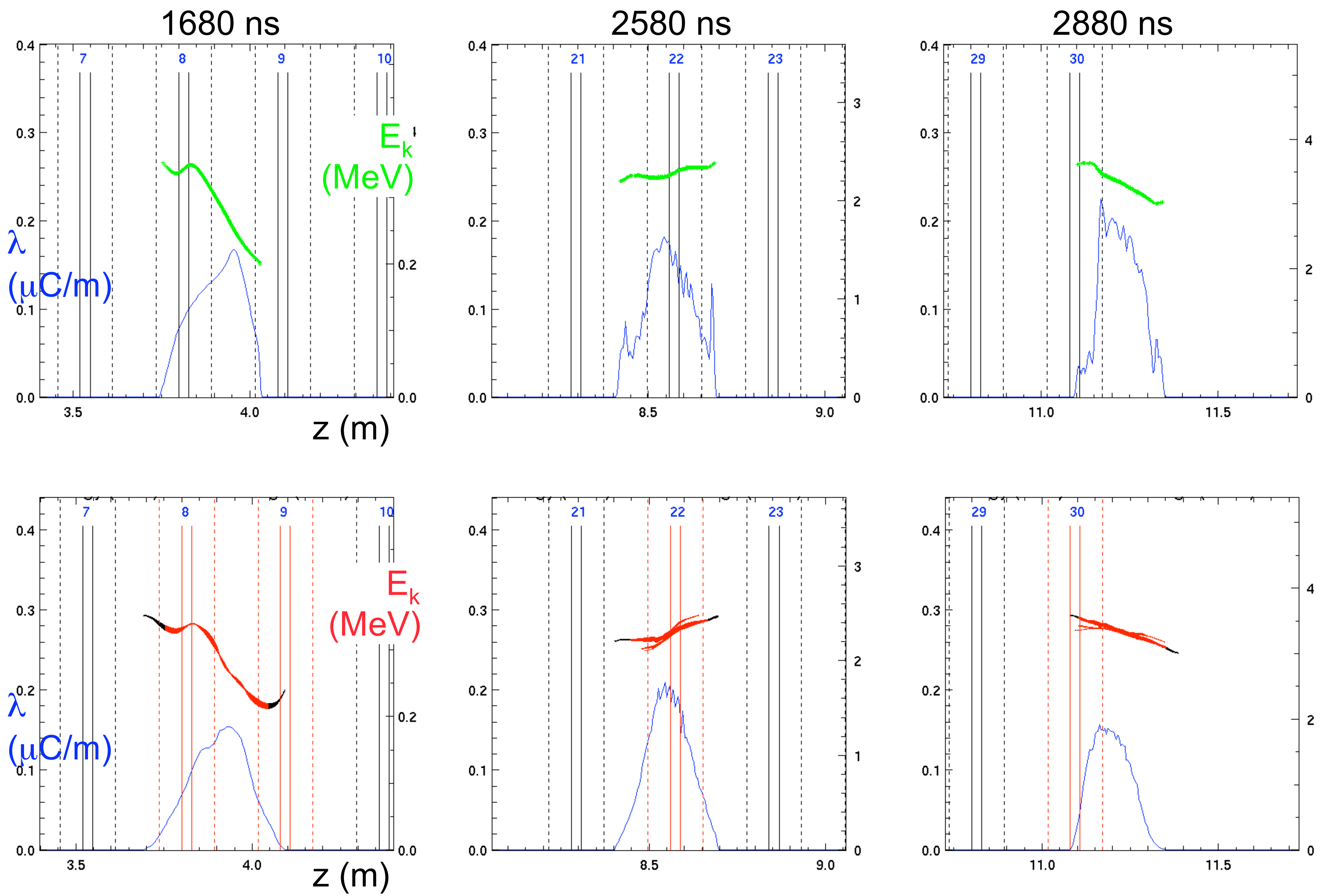
Longitudinally: the goal is achieved; most of the beam's 0.1 J passes through the target plane in ~1.2 ns



Transversely: peak fluence of 17 J/cm^2 is less than the 30 J/cm^2 desired; 78% of beam falls within a 1 mm spot



1-D code (top) & Warp (bottom) results agree, with differences



We look forward to a novel and flexible research platform

- The design concept is compact and attractive
  - It applies rapid bunch compression and acceleration
  - It makes maximal use of ATA induction modules and pulsed power
  - Beam emittance is well preserved in simulations

… but considerable work remains before this is a true “physics design”

- NDCX-II will be able to deliver far greater beam energy and peak power for Warm Dense Matter physics than NDCX-I

- We will soon begin to develop an NDCX-II acceleration schedule that delivers a ramped-energy beam, for energy coupling and hydrodynamics studies relevant to direct-drive Heavy Ion Fusion

Extras

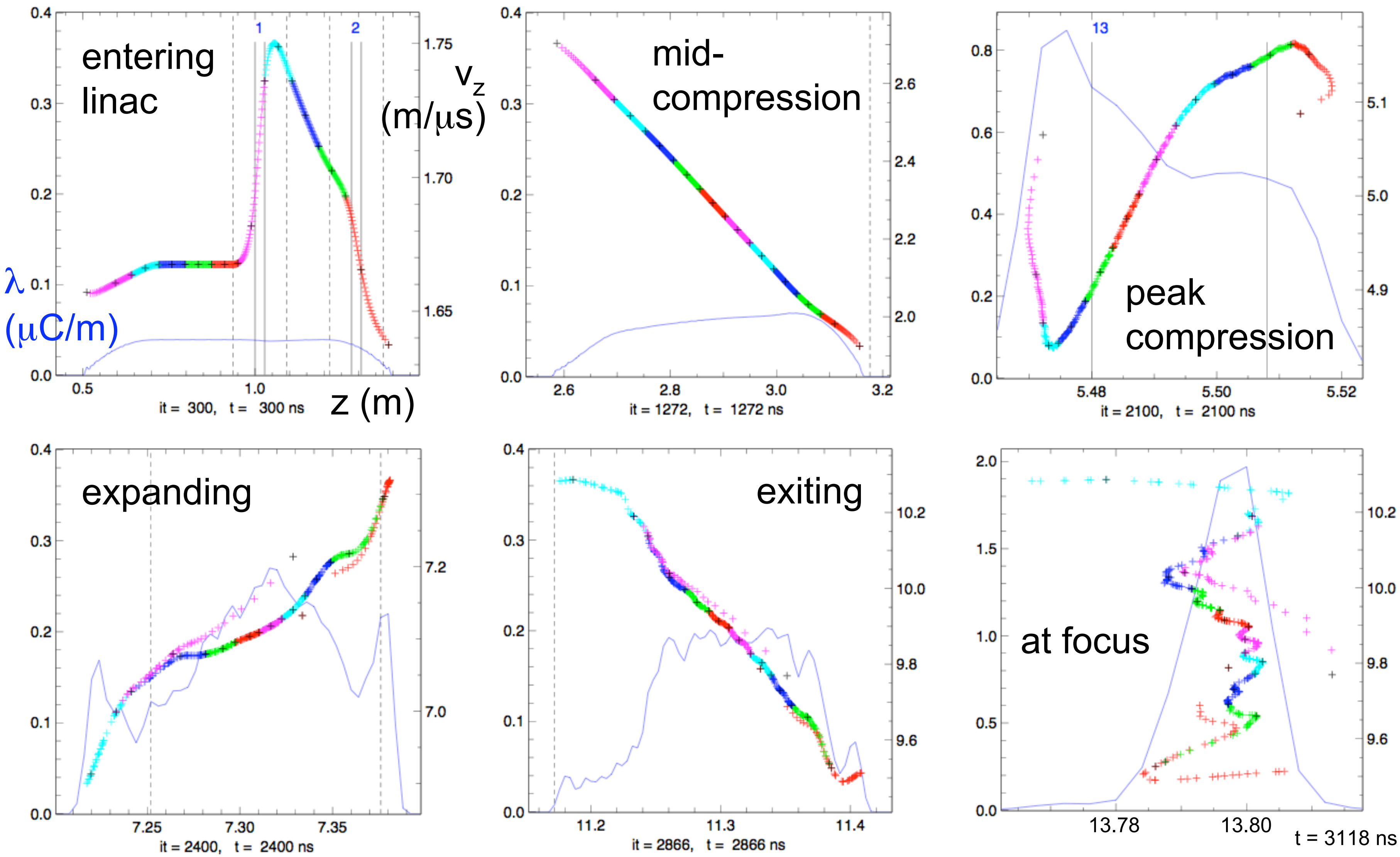
Progress has been encouraging; much remains to be done

- Proper accounting for initial beam-end energy variation due to space charge (the 1-D run shown was initiated with a fully-formed uniform-energy beam)
  - Other 1-D runs used a “model” initial energy variation and an entry “ear” cell; they produced compressed beams similar to the one shown
  - However, that variation was not realistic; a Warp run using the 1-D-derived waveforms yielded inferior compression
- Better understanding of beam-end wrap-around (causes and consequences)
- A prescription for setting solenoid strengths to yield a well-matched beam
- Optimized final focusing, accounting for dependence of the focal spot upon velocity tilt, focusing angle, and chromatic aberration
- Assessment of time-dependent focusing to correct for chromatic effects
- Development of plasma injection & control for neutralized compression & focusing (schemes other than the existing FCAPS may prove superior)
- Establishment of tolerances for waveforms and alignment

Major goals remain:

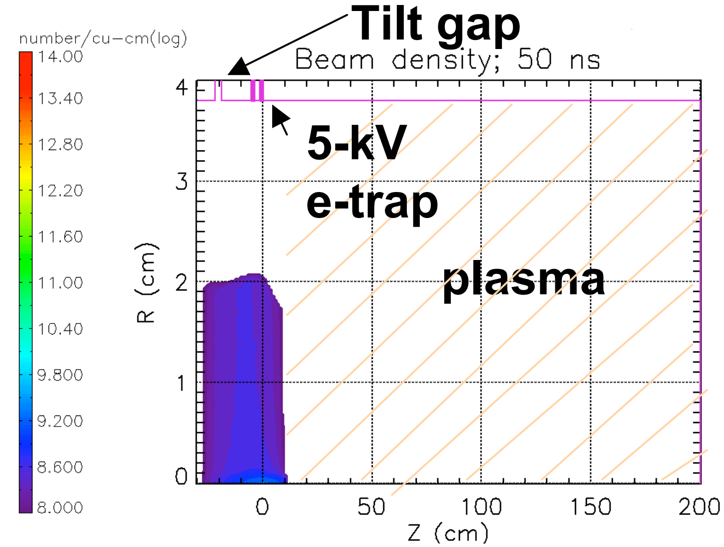
- a self-consistent source-through-target design, including assessment of tolerances etc., for WDM studies
- a prescription for modifications offering multiple pulses, ramped energy, and/or greater total energy, for ion direct drive studies

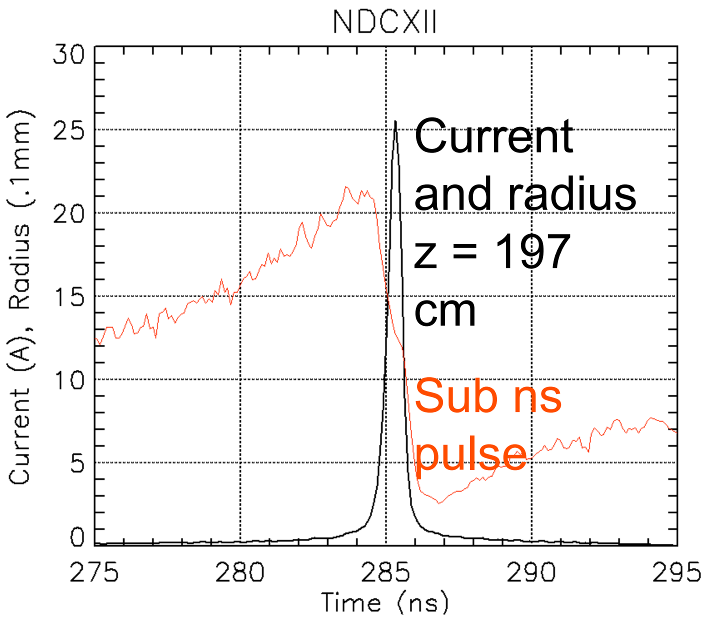
These snapshots show how the (v_z,z) phase space and the line charge density evolve (note the auto-scaling)

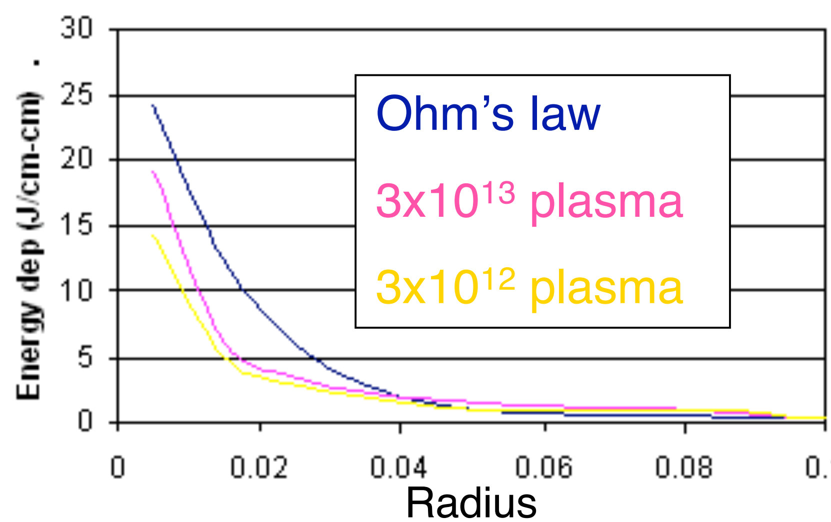


Simulations of NDCX-II neutralized compression and focus suggest that a plasma of density ~ 10^{14} cm^{-3} is desirable

- Idealized beam, uniform plasma, so far:
  - Li^{+}, 2.8 MeV, 1.67 eV temperature
  - 2-cm -5 or -6.7 mrad convergence
  - uniform current density; ε = 24 mm-mrad
  - 0.7-A with parabolic 50-ns profile
  - applying ideal tilt for 30 ns of beam
- ½ mm 1-ns beam has 2×10^{13} cm^{-3} density

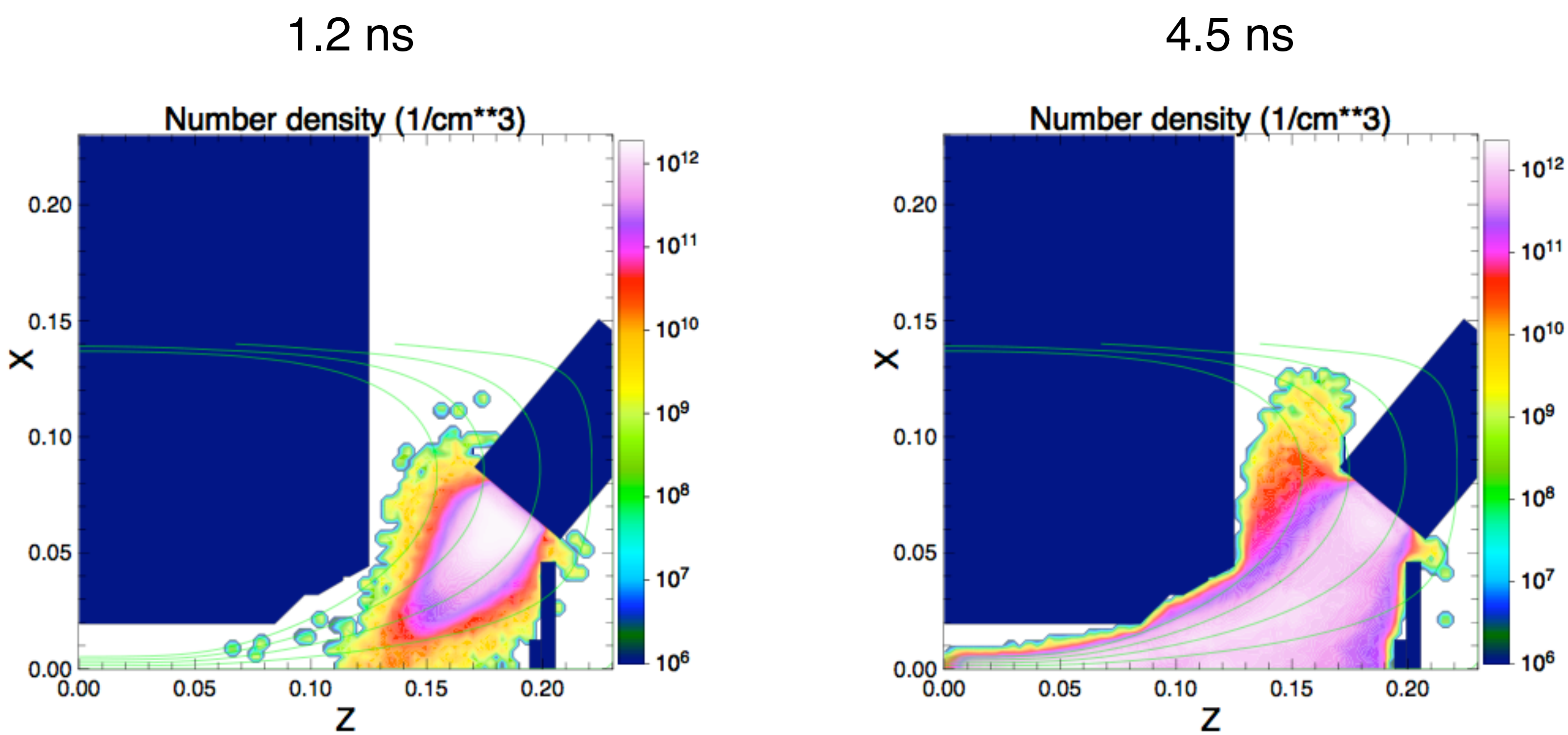






(LSP runs by D. Welch; others by A. Sefkow, M. Dorf; Warp code starting to be used)

We simulate injection from Cathodic-Arc Plasma sources



- This run corresponds to an NDCX-I configuration with 4 sources
- It was made by Dave Grote using Warp in 3-D mode
- LSP has been used extensively for such studies