# Overview of NDCX-II Physics Design

and

# Comments on final beam-lines for a driver*


Alex Friedman

Fusion Energy Program, LLNL
and
Heavy Ion Fusion Science Virtual National Laboratory


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The Heavy Ion Fusion Science Virtual National Laboratory


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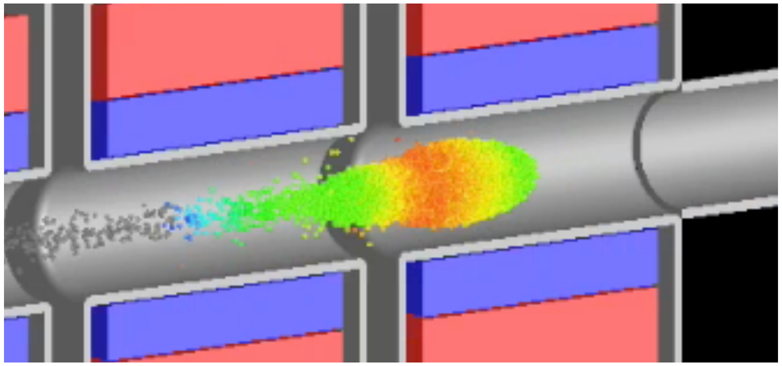
# Overview of NDCX-II Physics Design



*Beam traversing an acceleration gap*

# 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

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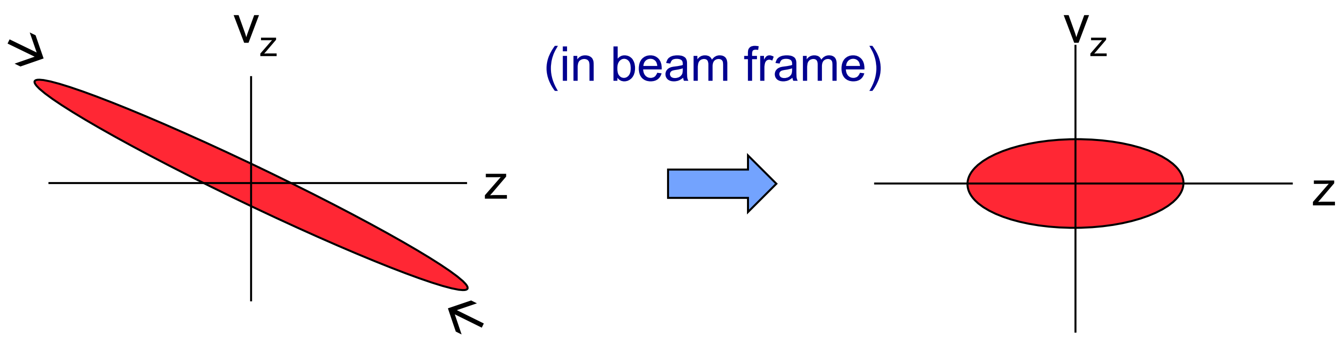
- In non-neutral drift compression, the space charge force opposes (“stagnates”) the inward flow, leading to a nearly mono-energetic compressed pulse:

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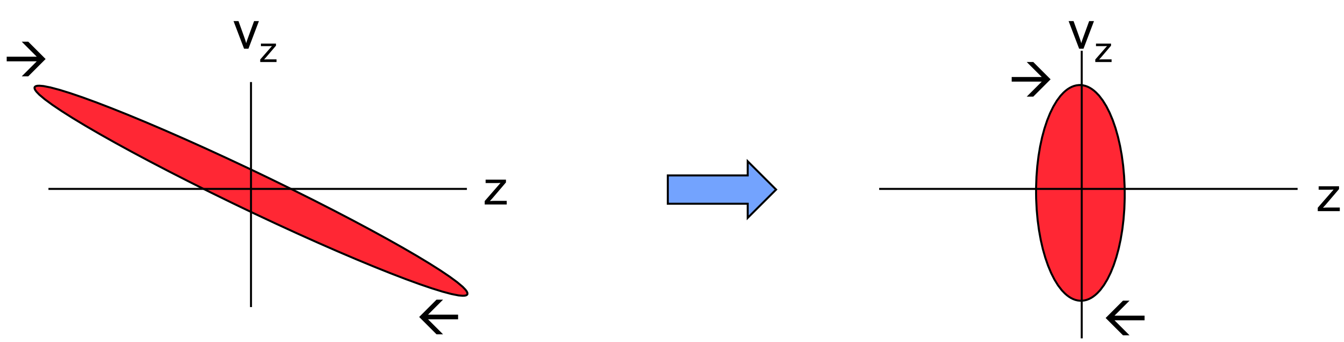
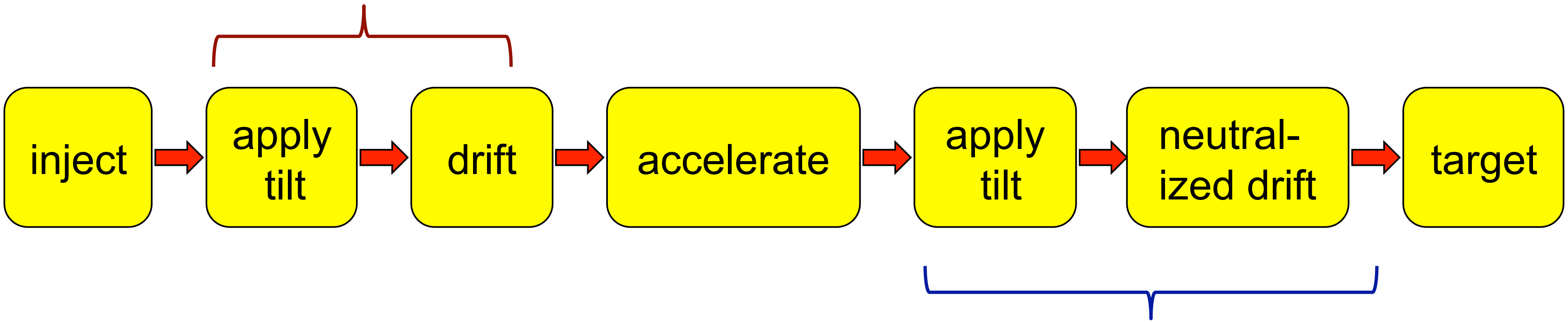
- In neutralized drift compression, the space charge force is eliminated, resulting in a shorter pulse but a larger velocity spread:



# Drift compression is used twice in NDCX-II

Initial non-neutral pre-bunching for:

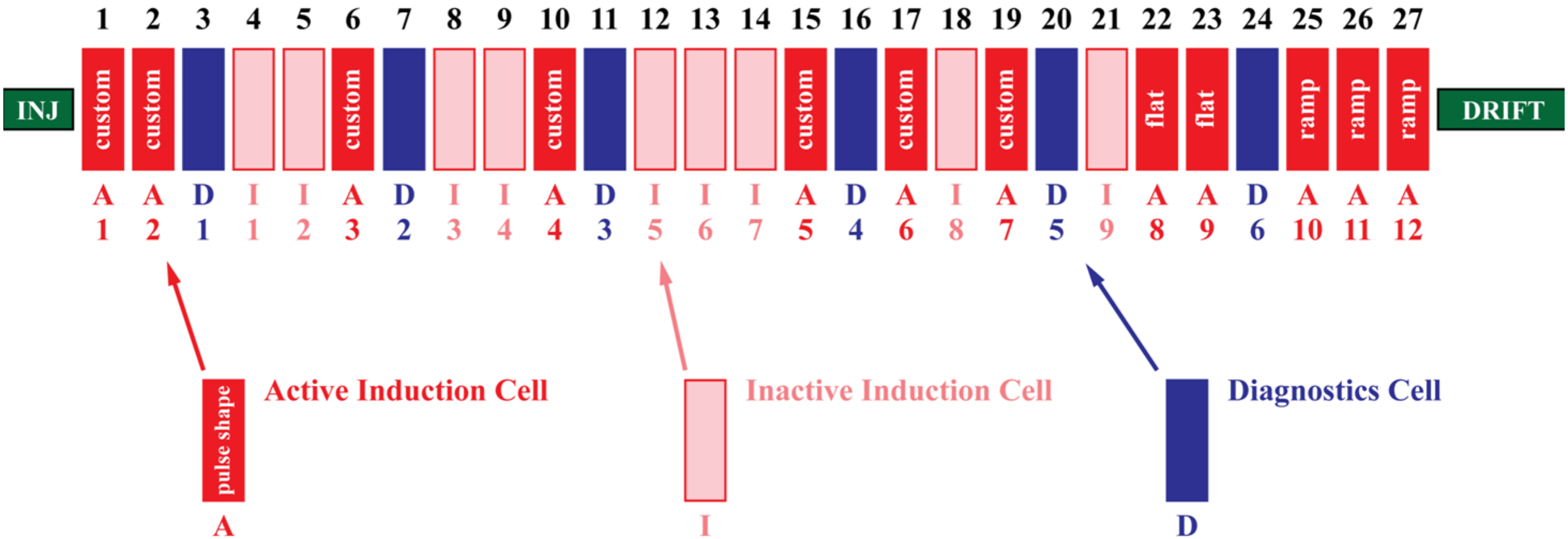
- better use of induction-core Volt-seconds
- early use of 70-ns 250-kV Blumlein power supplies from ATA




Final neutralized drift compression onto the target

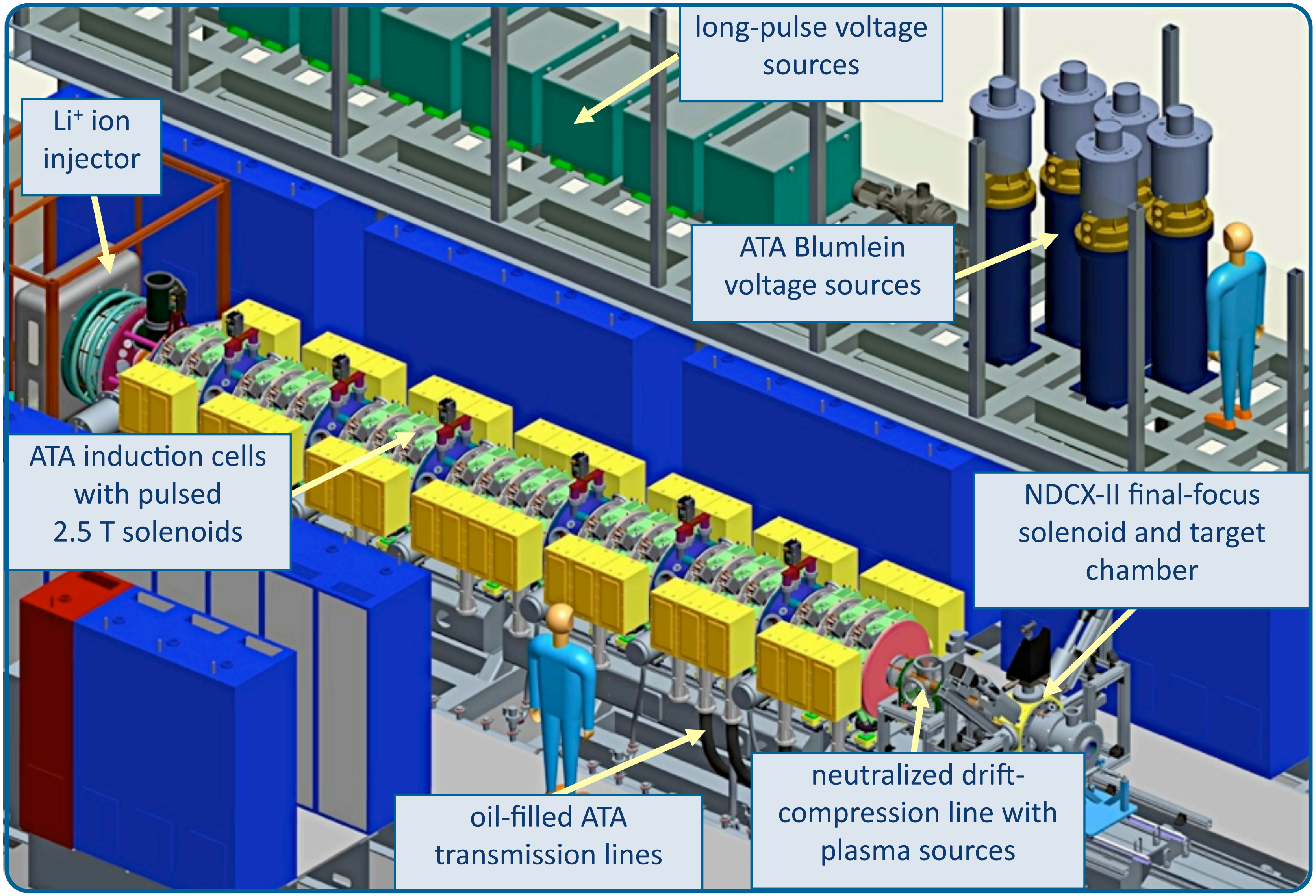
- Electrons in plasma move so as to cancel the beam’s electric field
- Require $n_{plasma} > n_{beam}$ for this to work well

# The baseline hardware configuration is as presented during the April 2010 DOE Project Review

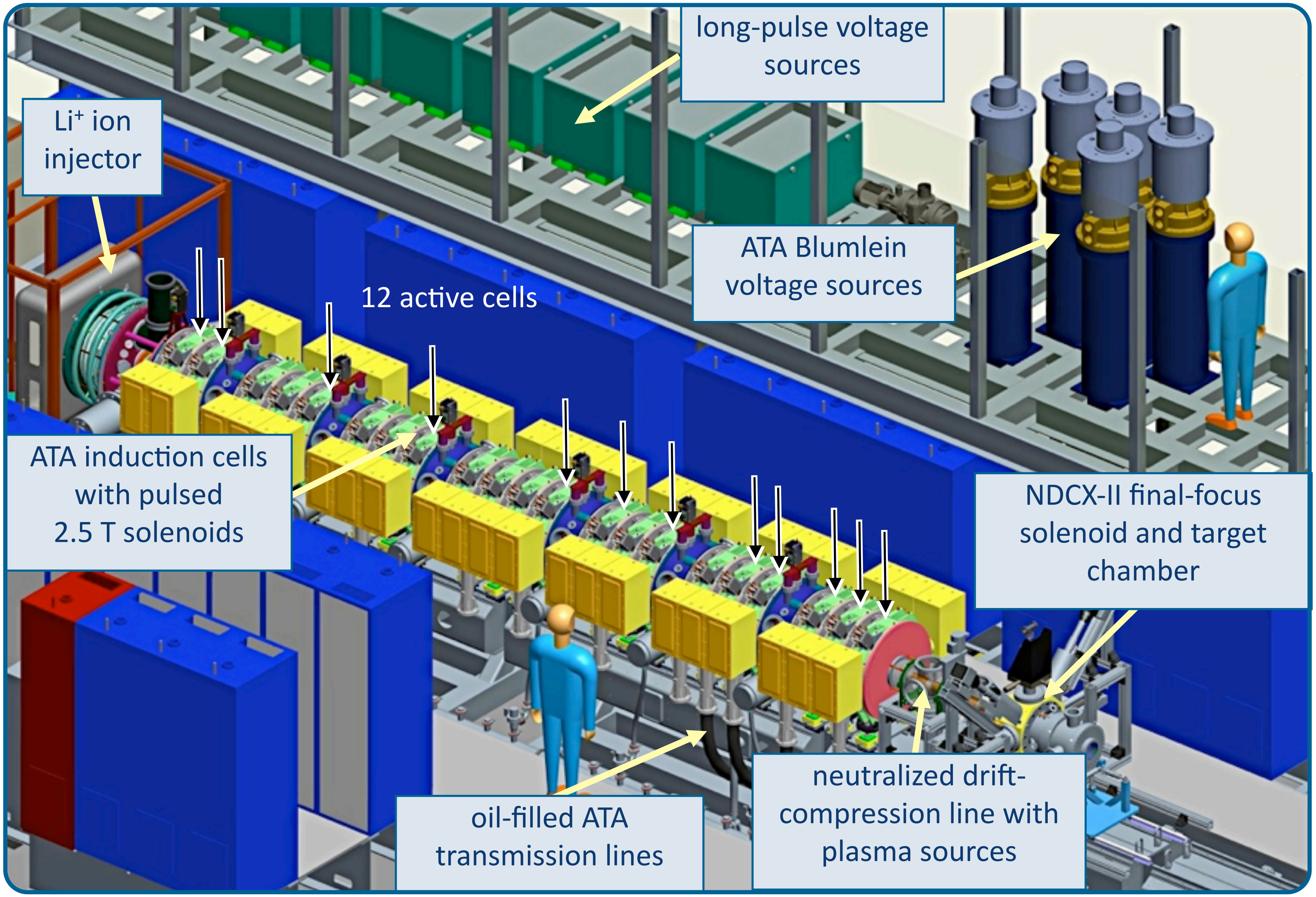



- 27 lattice periods after the injector
- 12 active induction cells
- Beam charge ~50 nano-Coulombs
- FWHM < 1 ns
- Kinetic energy ~ 1.2 MeV

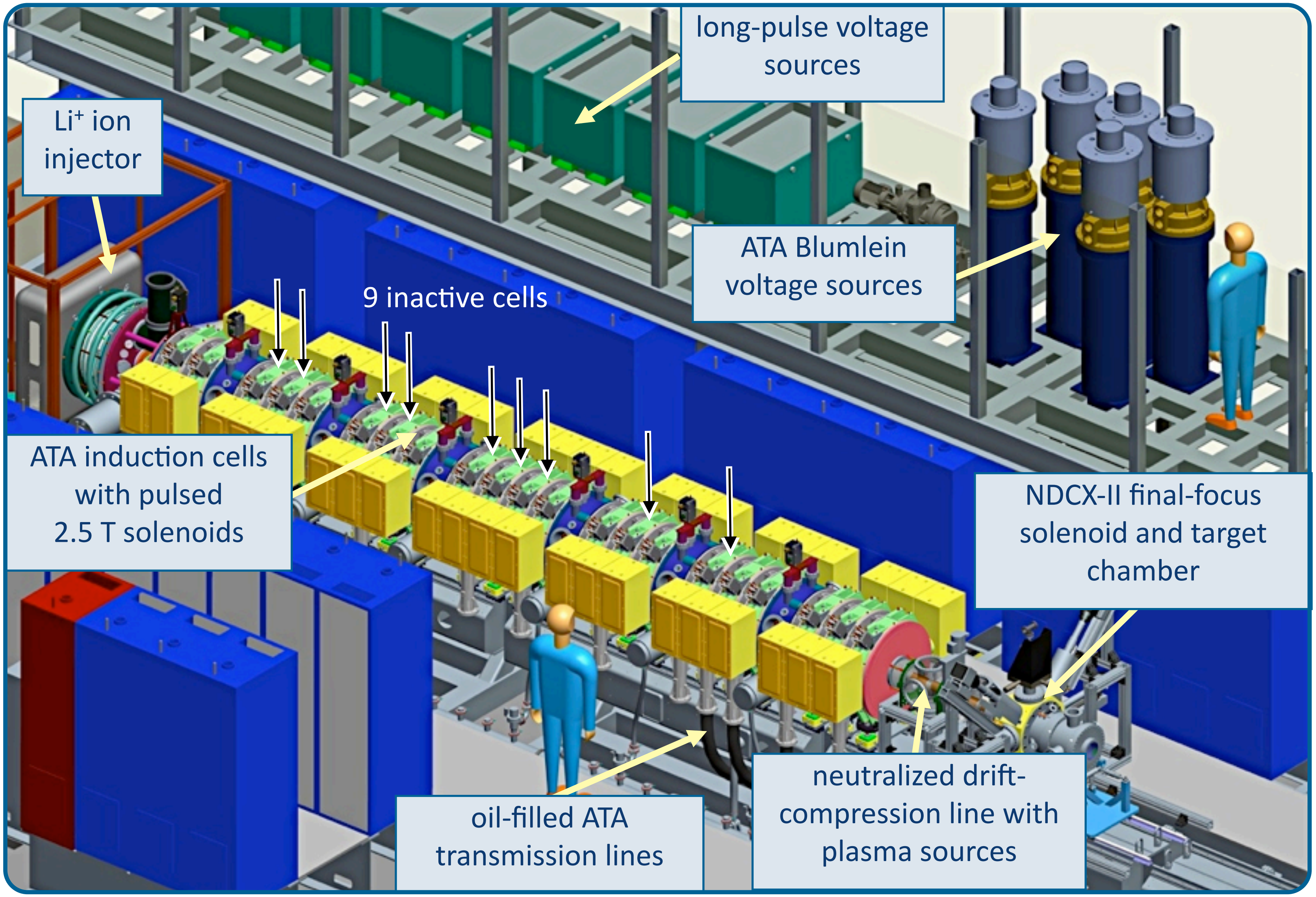
# 12-cell NDCX-II baseline layout



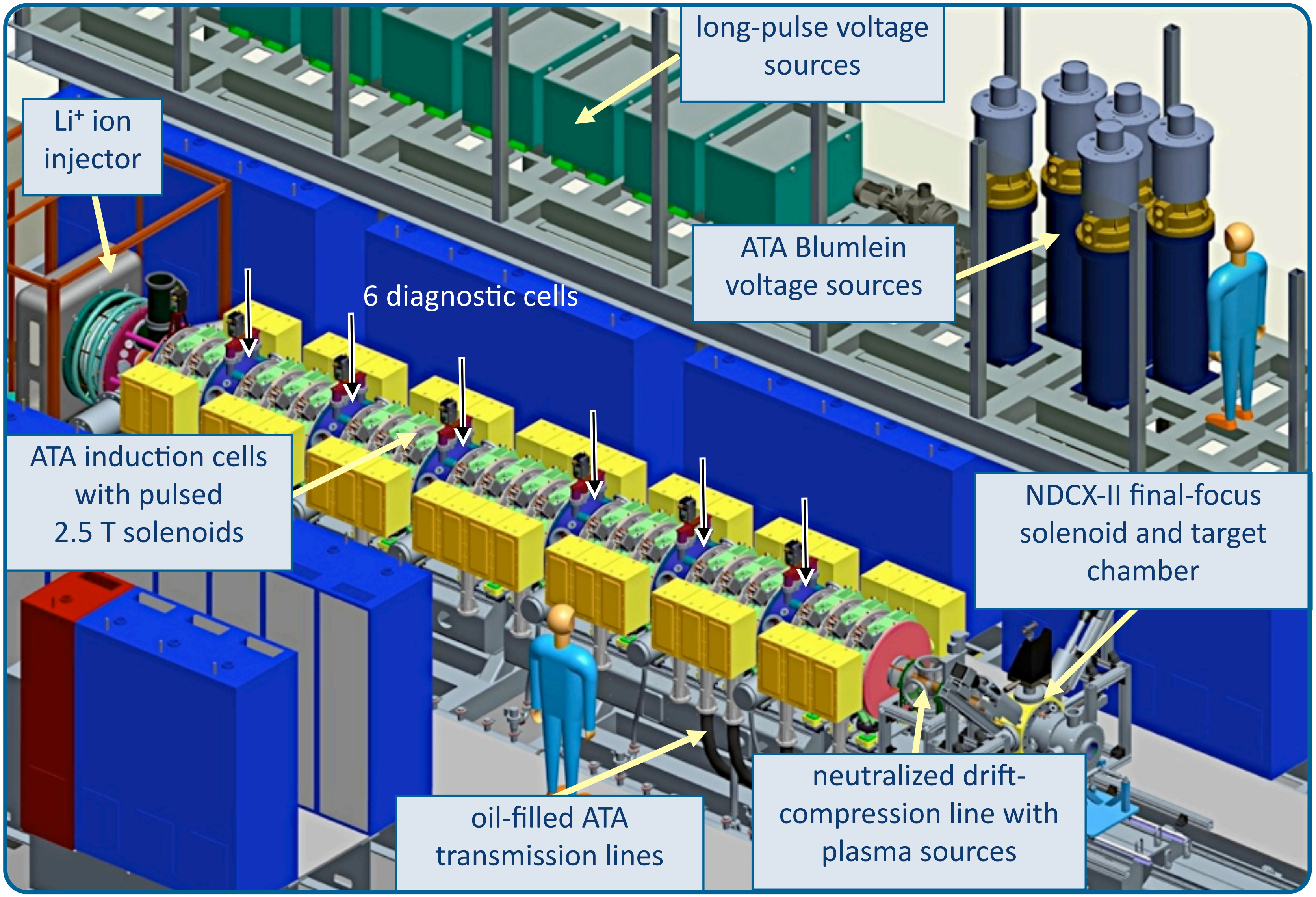
# 12-cell NDCX-II baseline layout



# 12-cell NDCX-II baseline layout

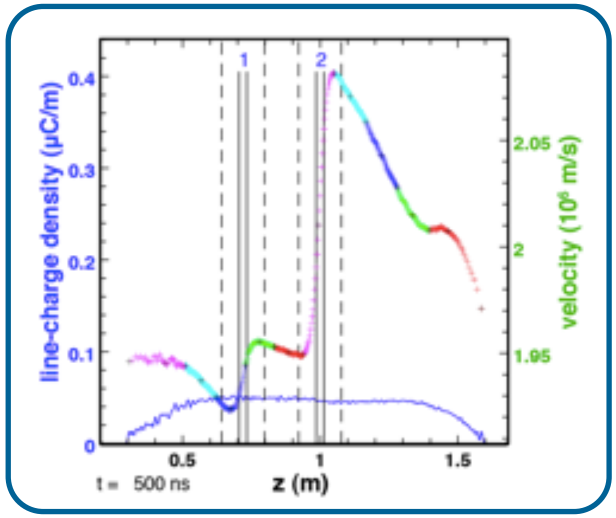


# 12-cell NDCX-II baseline layout

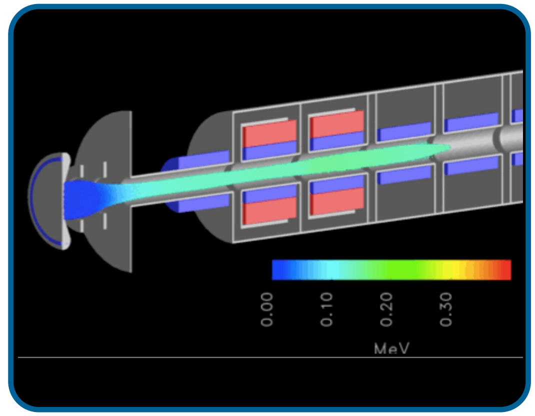


# Simulations enabled development of the NDCX-II physics design

- ASP is a purpose-built, fast 1-D (z) particle-in-cell code to develop acceleration schedules
  - 1-D Poisson solver, with radial-geometry correction
  - realistic variation of acceleration-gap fields with z
  - several optimization options



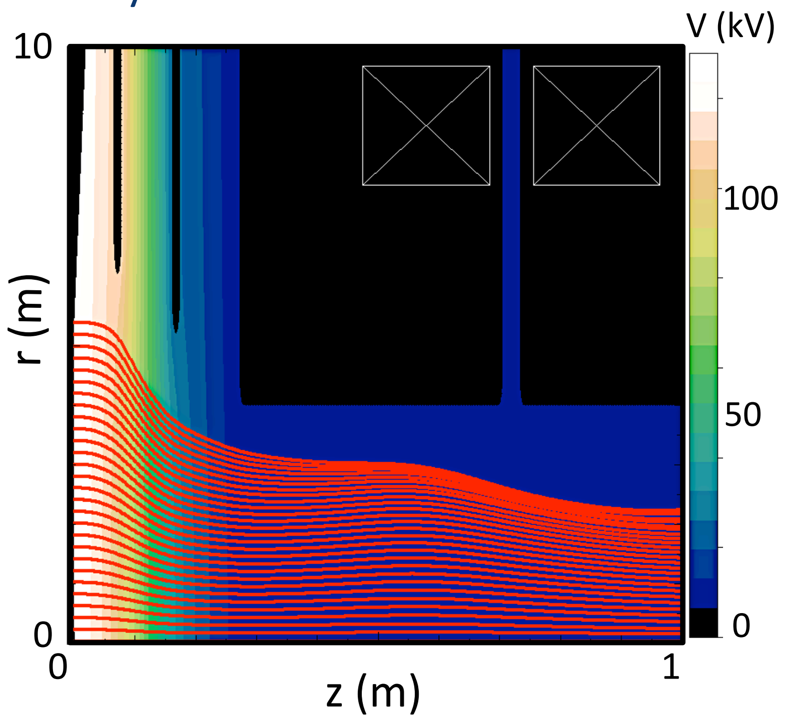

- Warp is our full-physics beam simulation code
  - 1, 2, and 3-D ES and EM field solvers
  - first-principles & approximate models of lattice elements
  - space-charge-limited and current-limited injection
  - cut-cell boundaries for internal conductors in ES solver
  - Adaptive Mesh Refinement (AMR)
  - large $\Delta t$ algorithms (implicit electrostatic, large $\omega_c\Delta t$)
  - emission, ionization, secondaries, Coulomb collisions...
  - parallel processing




A. Friedman, *et al.*, *Phys. Plasmas* **17**, 056704 (2010).

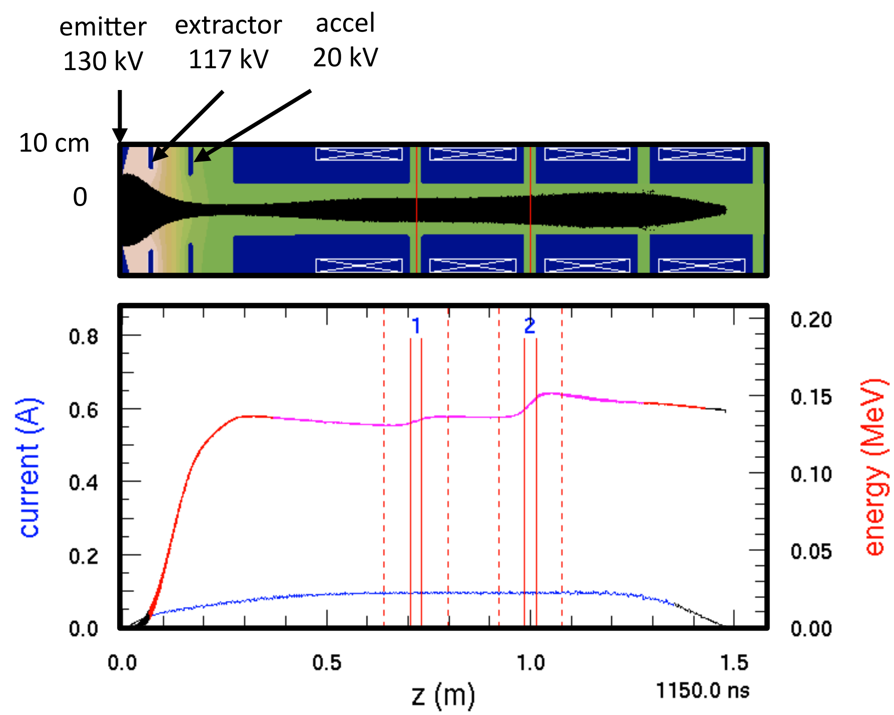
# Steps in development of the NDCX-II physics design …

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




1 mA/cm² Li⁺ ion source

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

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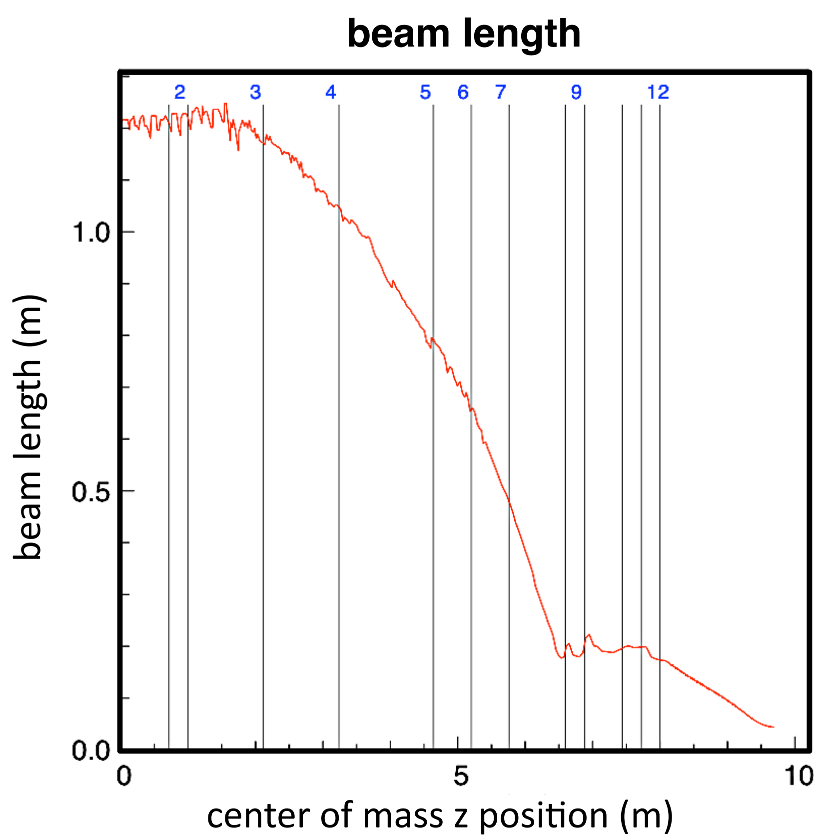
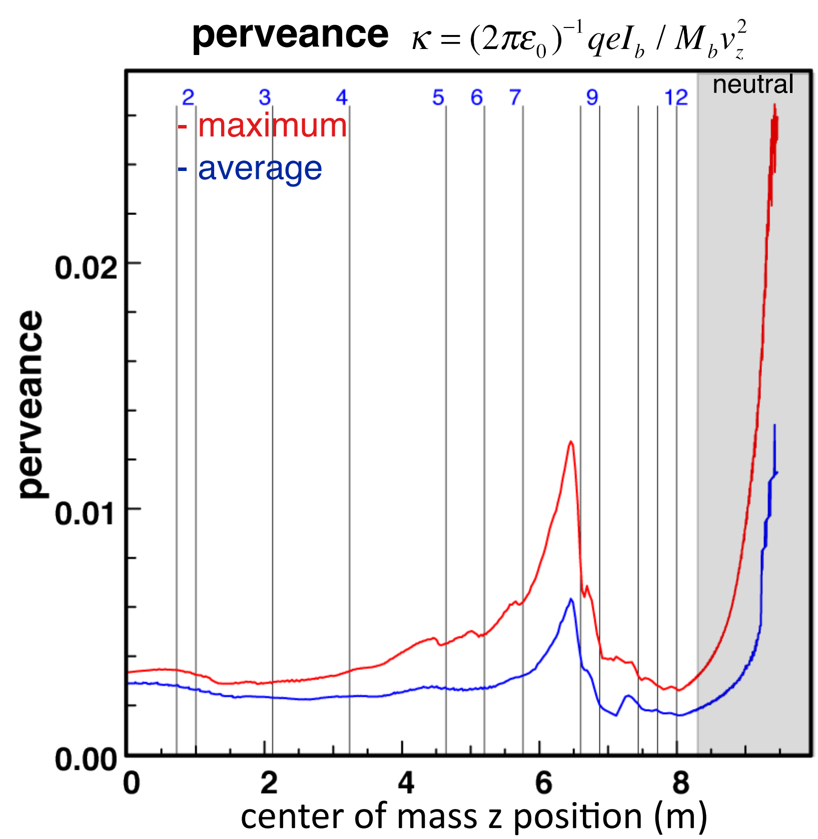
# Steps in development of the NDCX-II physics design …

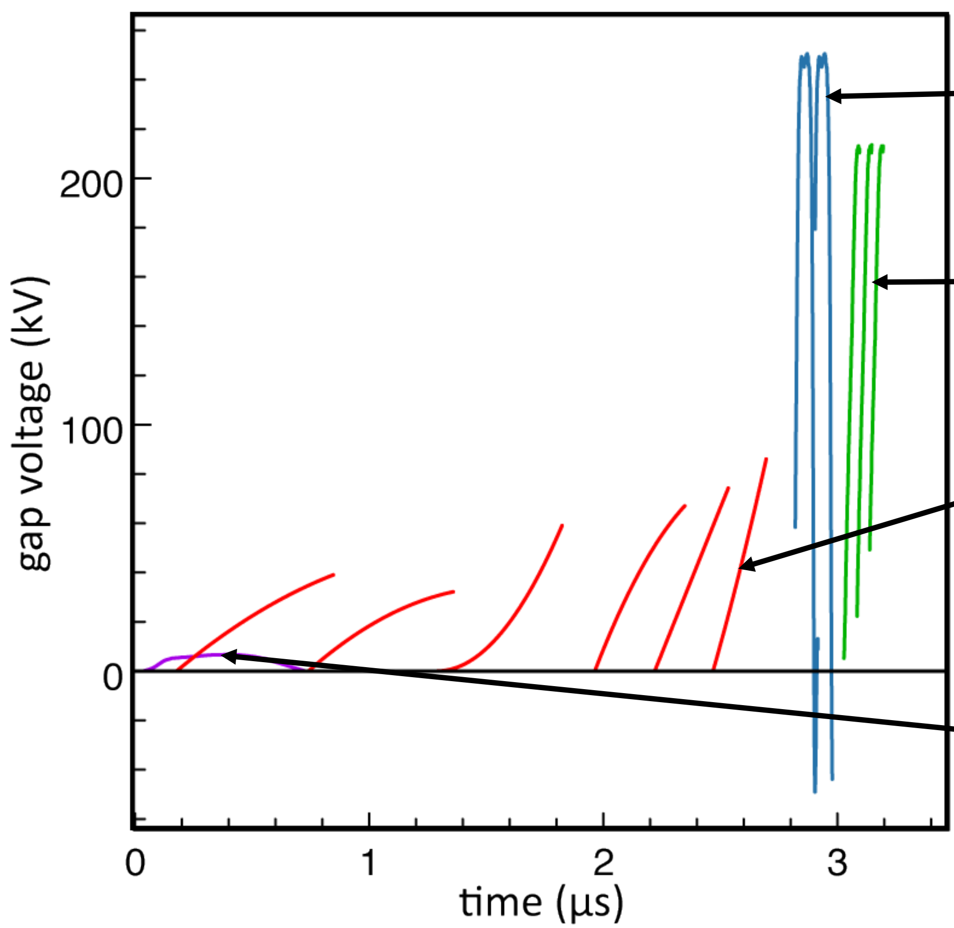
third, iterate with ASP to find an acceleration schedule that delivers a beam with an acceptable final phase-space distribution



# Steps in development of the NDCX-II physics design …

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




250 kV "flat-top" measured waveform from test stand

200 kV "ramp" measured waveform from test stand

"shaped" for initial bunch compression (scaled from measured waveforms)

"shaped" to equalize beam energy after injection

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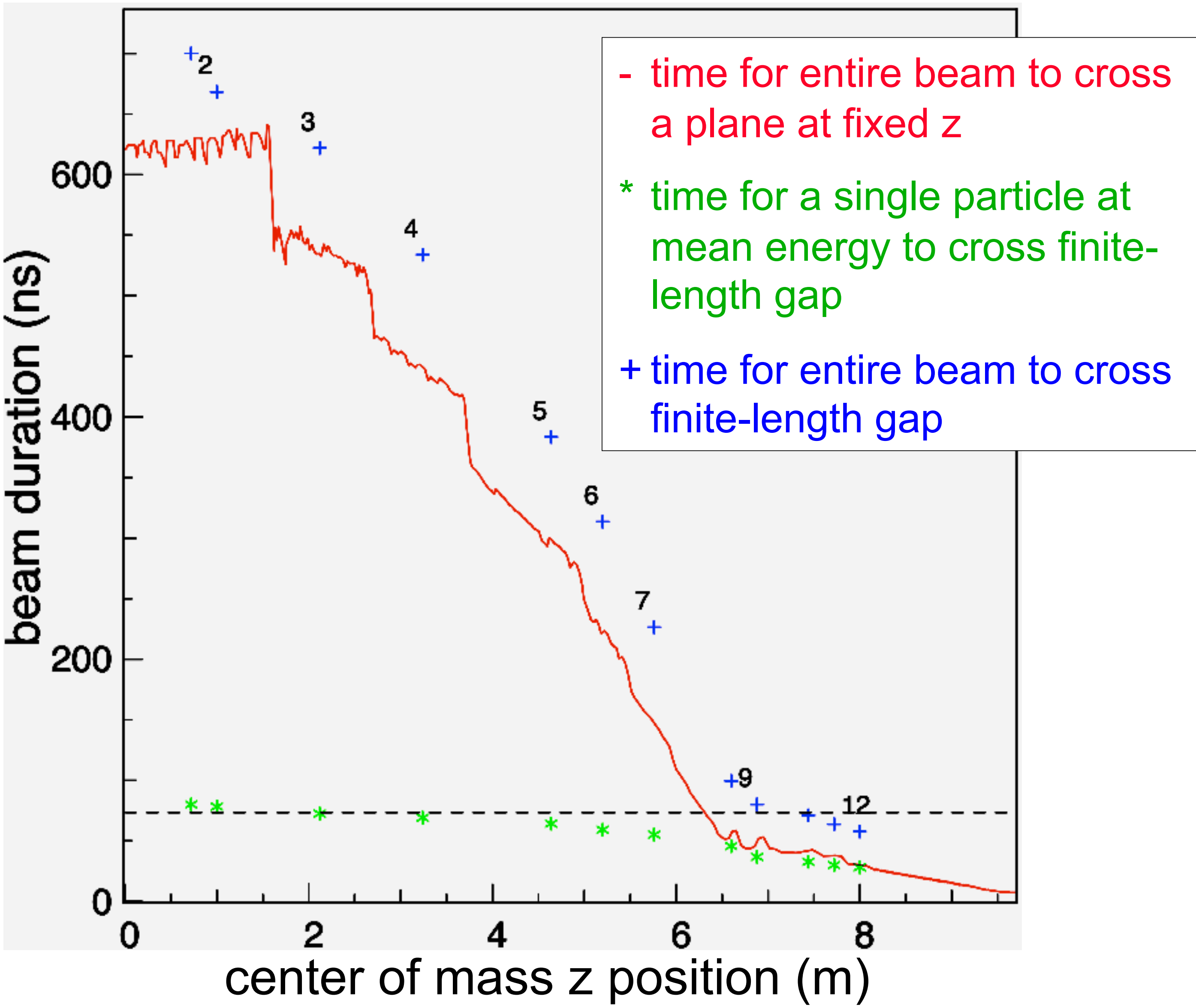
# Pulse duration vs. z: the finite length of the gap field folds in

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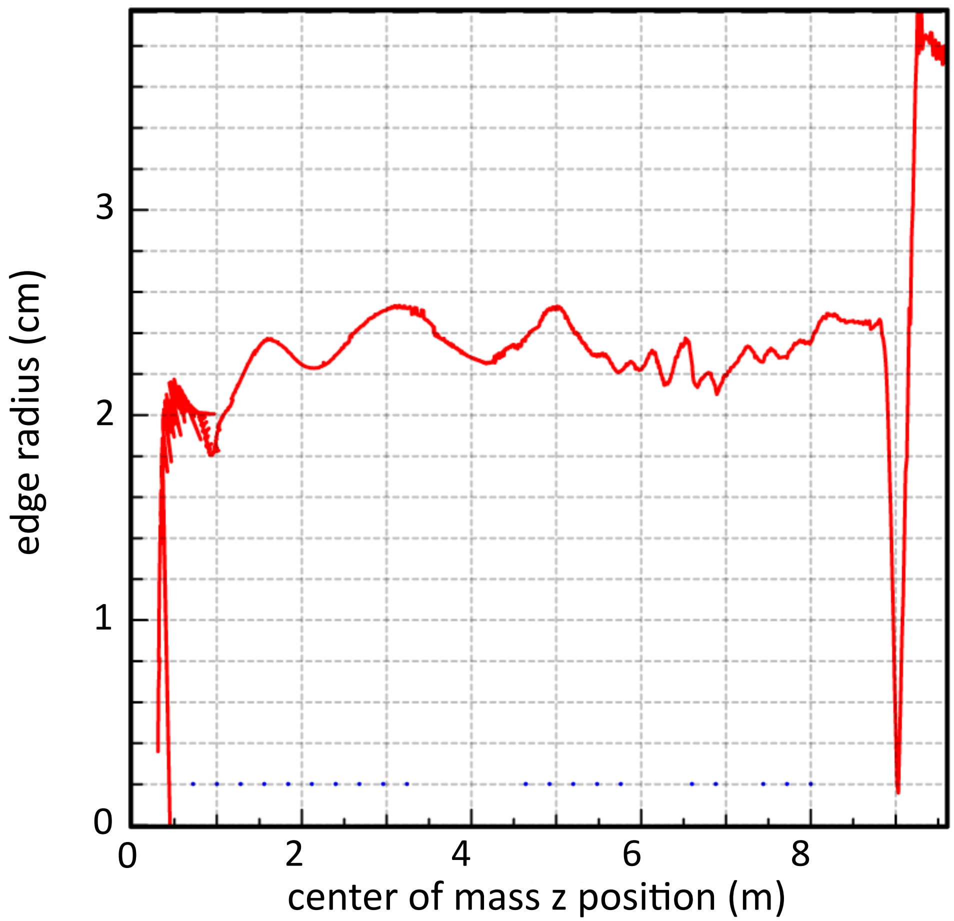
# Steps in development of the NDCX-II physics design …

fifth, adjust transverse focusing to maintain nearly constant radius

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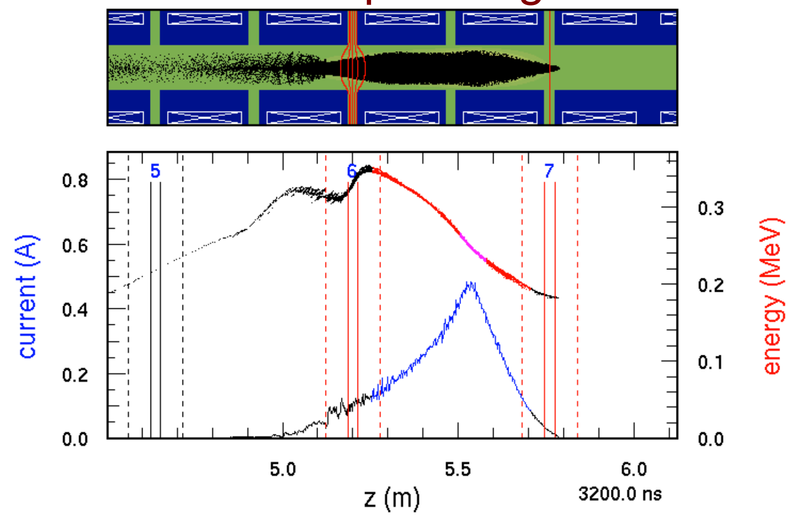
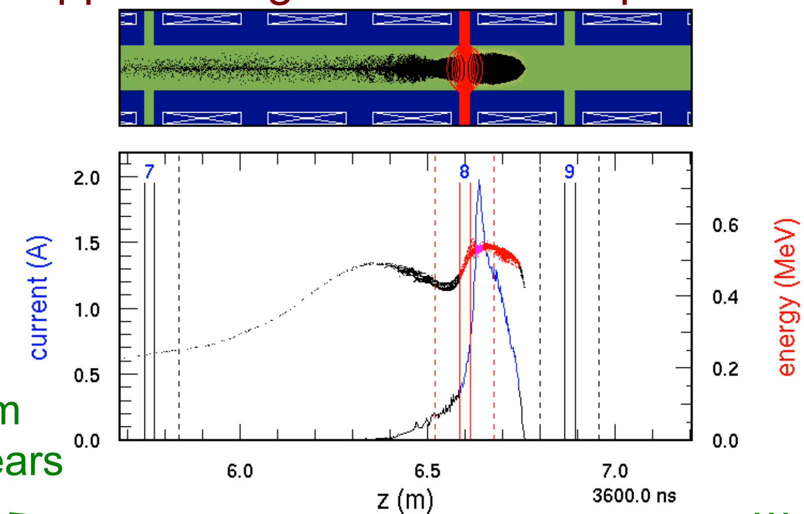
# Snapshots from a Warp (r,z) simulation

## compressing

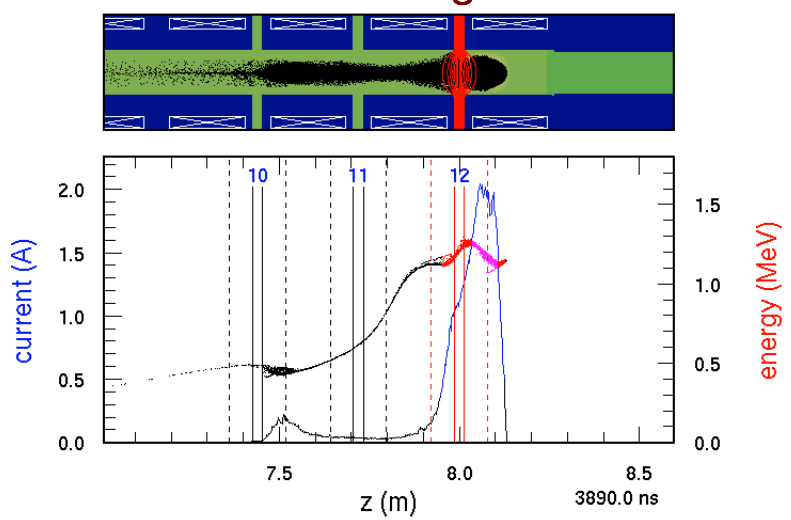



## approaching maximum compression

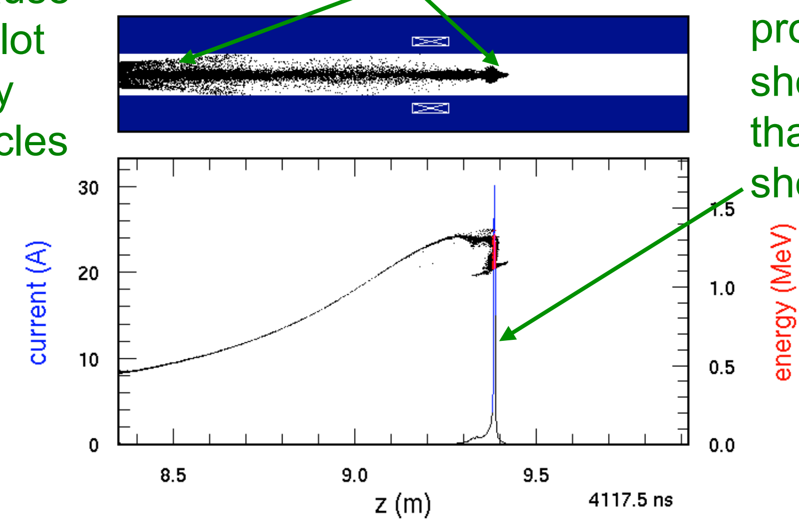



Beam appears long because we plot many particles …

## exiting




## at focus




… but current profile shows that it is short

40g-12



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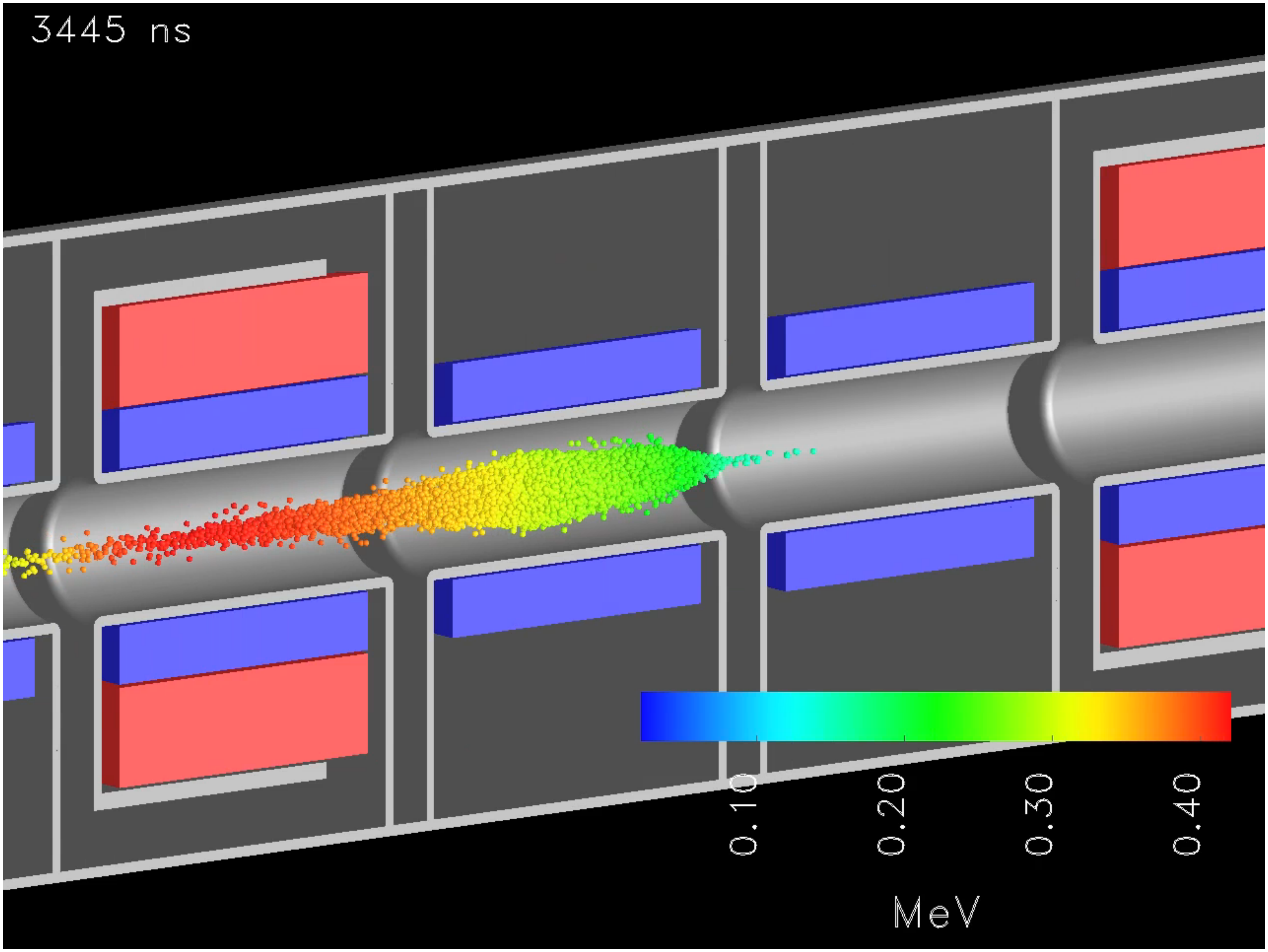
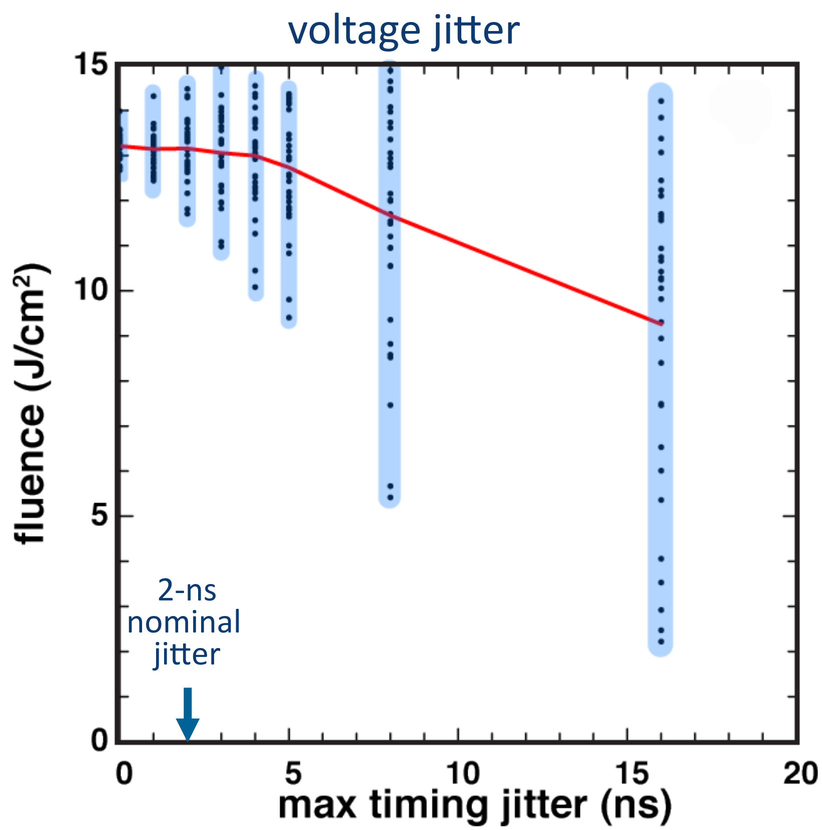
# 3-D Warp simulation with perfectly aligned solenoids




40ga24-12 simulation and movie from D P Grote

# Steps in development of the NDCX-II physics design …

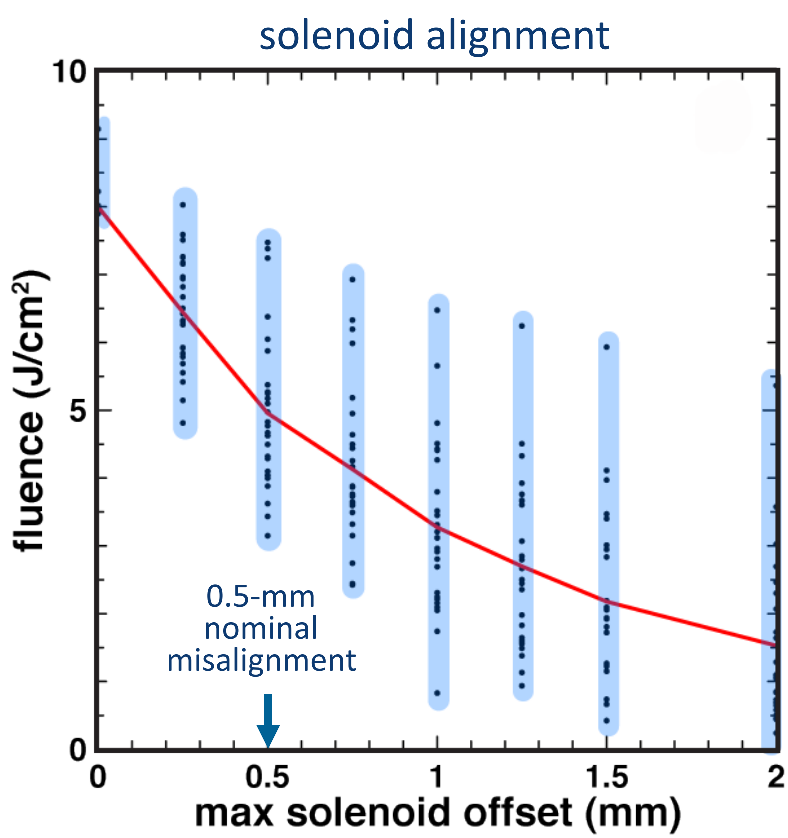
sixth, test sensitivity to random timing error in acceleration waveforms




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.

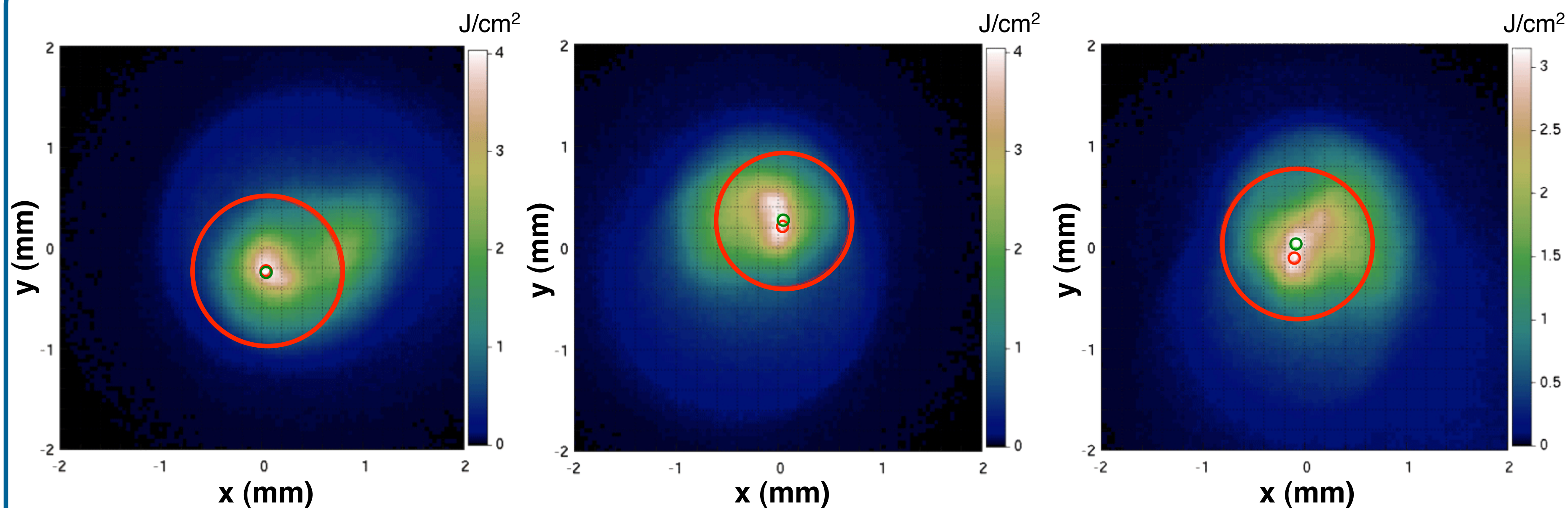
# Warp runs illustrate effects of solenoid alignment errors

plots show beam deposition for three ensembles of solenoid offsets

maximum offset for each case is 0.5 mm

red circles include half of deposited energy

smaller circles indicate hot spots

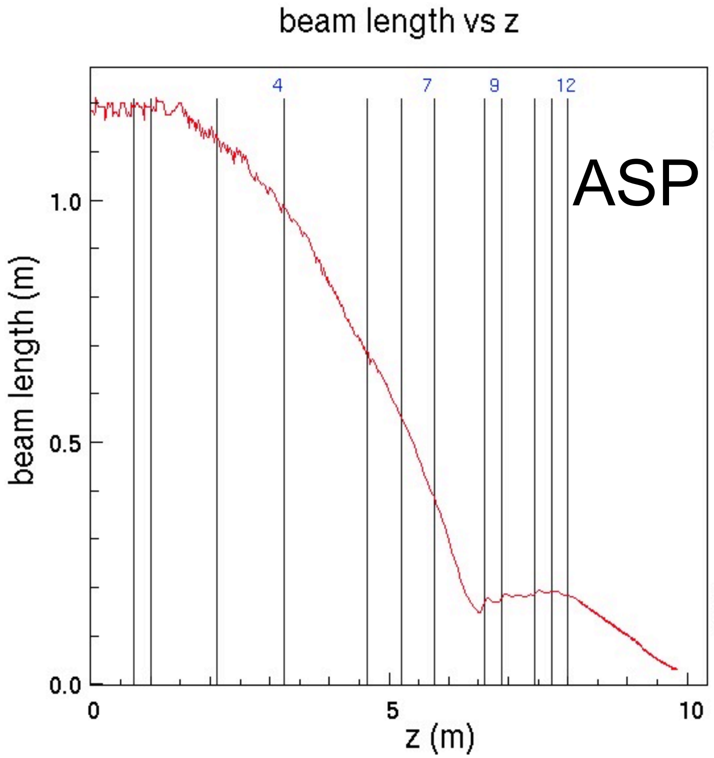


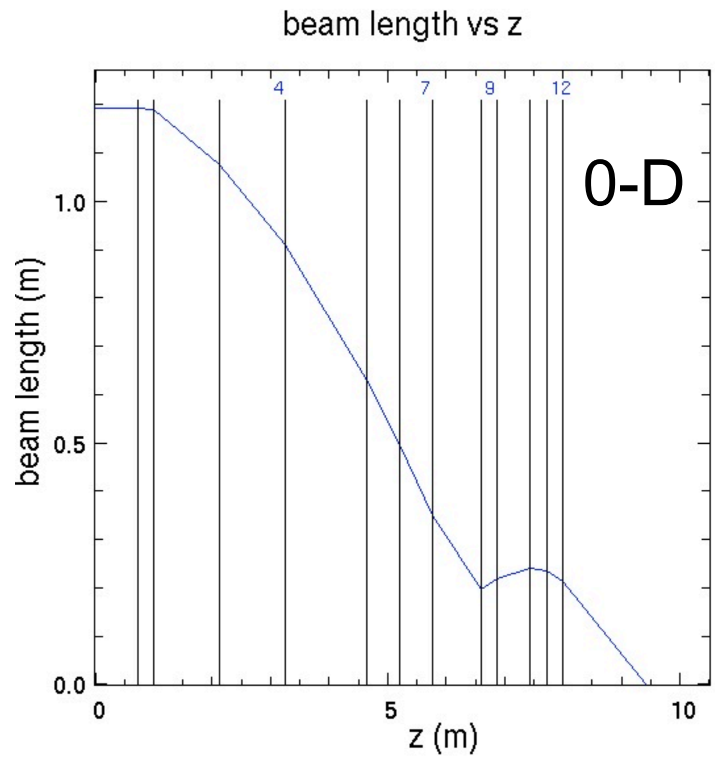

ASP and Warp runs show that steering can improve intensity and stabilize spot location

see Y-J Chen, et al., Nucl. Inst. Meth. in Phys. Res. A 292, 455 (1990)

# A "zero-dimensional" Python code (essentially, a spreadsheet) captures the essence of the NDCX-II acceleration schedule

- Computes energy jumps of nominal head and tail particles at gaps
- Space-charge-induced energy increments between gaps via a "g-factor" model




- The final head and tail energies (keV) are off; the g-factor model does not accurately push the head and tail outward:
- But – not bad, for a main loop of 16 lines.

| | 0-D | ASP |
|---|---|---|
| head | 923 | 1100 |
| tail | 1082 | 1300 |

# Things we need to measure, and the diagnostics we'll use

Non-intercepting (in multiple locations):

- Accelerating voltages: voltage dividers on cells
- Beam transverse position: four-quadrant electrostatic capacitive probes
- Beam line charge density: capacitive probes
- Beam mean kinetic energy: time-of-flight to capacitive probes

Intercepting (in two special "inter-cell" sections):

- Beam current: Faraday cup
- Beam emittance: two-slit or slit-scintillator scanner
- Beam profile: scintillator-based optical imaging
- Beam kinetic energy profile: time-of-flight to Faraday cup
- Beam energy distribution: electrostatic energy analyzer

*(Underlined items will be available at commissioning)*

# “Physics risks” concern beam intensity on target, not project completion or risk to the machine due to beam impact

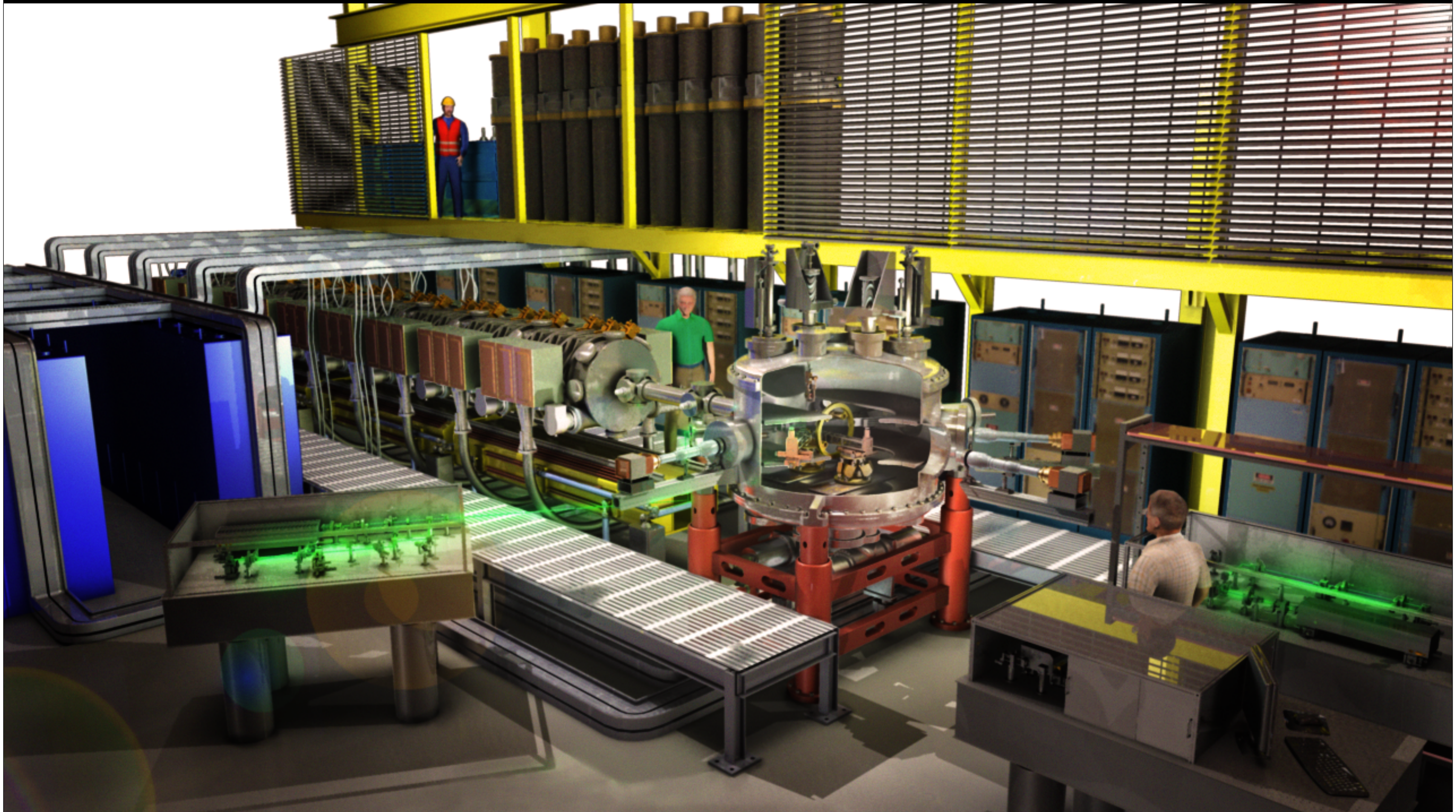
- Alignment errors exceeding nominal 0.5 mm
  - Machine usable with larger errors with intensity degradation
  - Beam “steering,” using dipoles in diagnostic cells, can mitigate “corkscrew” deformation of beam
  - Off-center beam, if reproducible, is not a significant issue
- Jitter of spark-gap firing times exceeding nominal 2 ns
  - Slow degradation of performance with jitter expected, per simulations
  - Similar slow degradation as waveform fidelity decreases
- Source emission non-uniform, or with density less than nominal 1 mA/cm$^2$
  - Simulations show a usable beam at 0.5 mA/cm$^2$
  - Will run in this mode initially, to maximize source lifetime
  - Space-charge-limited emission mode offers best uniformity
- Imperfect neutralization because final-focus solenoid not filled with plasma
  - Build and use a larger-radius solenoid at modest cost to program

# NDCX-II, when mature, should be far more capable than NDCX-I

| | NDCX-I (typical bunched beam) | NDCX-II 12-cell (ideal*) |
|---|---|---|
| Ion species | $K^+$ (A=39) | $Li^+$ (A=7) |
| Total charge | 15 nC | 50 nC |
| Ion kinetic energy | 0.3 MeV | 1.25 MeV |
| Focal radius (containing 50% of beam) | 2 mm | 0.6 mm |
| Bunch duration (FWHM) | 2 ns | 0.6 ns |
| Peak current | 3 A | 38 A |
| Peak fluence (time integrated) | 0.03 J/cm$^2$ | 8.6 J/cm$^2$ |
| Fluence within a 0.1 mm diameter spot | 0.03 J/cm$^2$ (50 ns window) | 5.3 J/cm$^2$ (0.57 ns window) |
| Fluence within 50% focal radius and FWHM duration ($E_{kinetic}$ x I x t / area) | 0.014 J/cm$^2$ | 1.0 J/cm$^2$ |

* NDCX-II estimates of ideal performance are from (r,z) Warp runs (no misalignments), and assume uniform 1 mA/cm$^2$ ion emission, no timing or voltage jitter in acceleration pulses, no jitter in solenoid excitation, and perfect beam neutralization; they also assume no fine energy correction (e.g., tuning the final tilt waveforms)

# NDCX-II will be a unique user facility for HIF-relevant physics.



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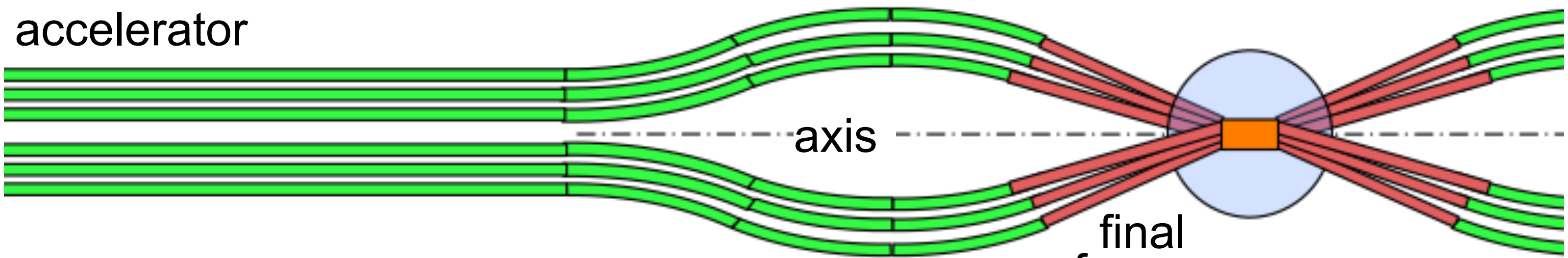
# Comments on final beam-lines for a driver

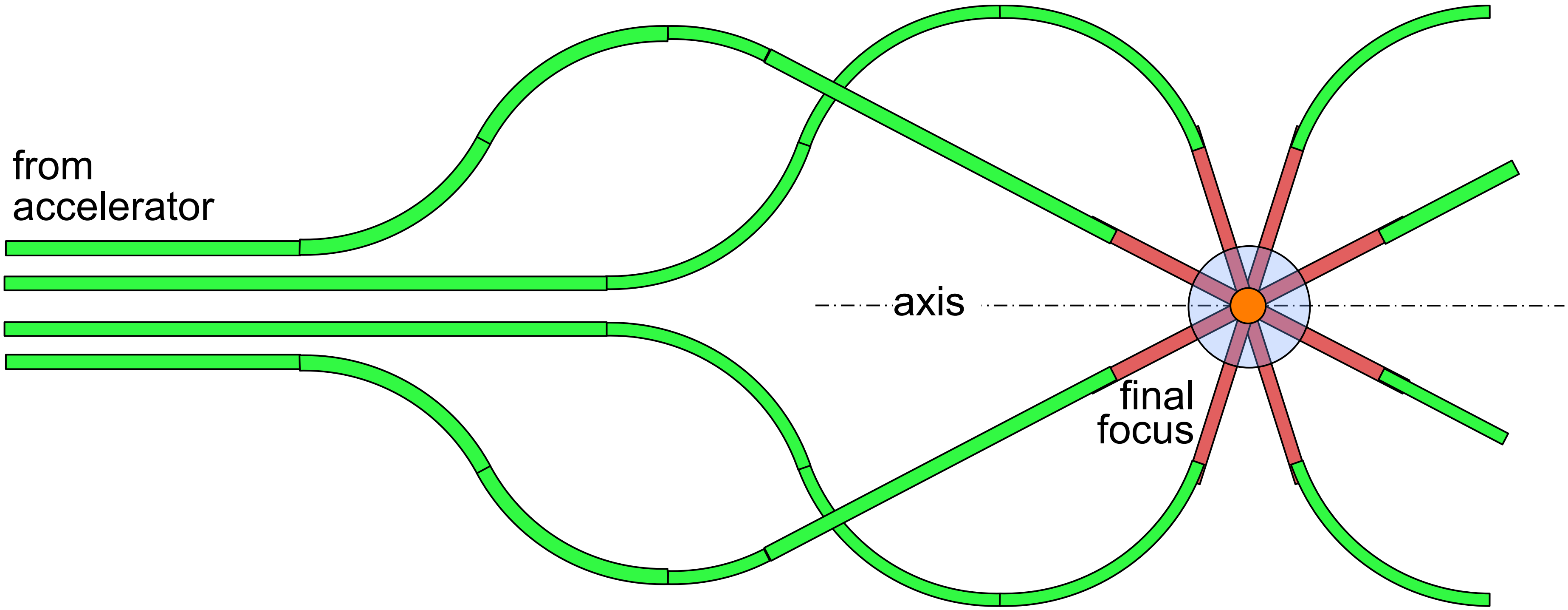
# Schematic of final beamlines for ion indirect drive

(only representative
beamlines are shown)



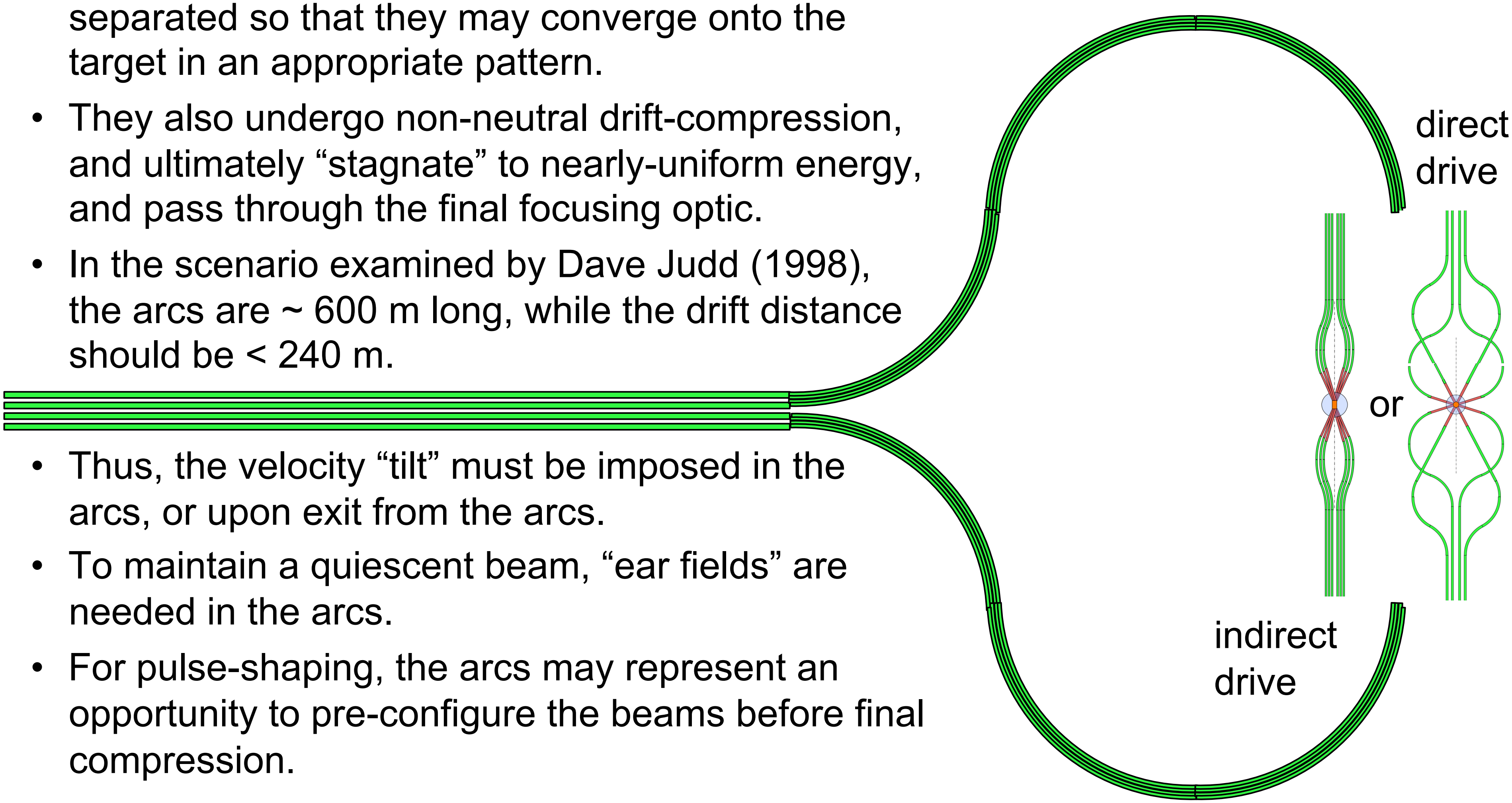
# Schematic of final beamlines for ion direct drive

(only representative beamlines are shown)



# With a single linac, arcs transport the beams to the two sides of the target (for most target concepts)

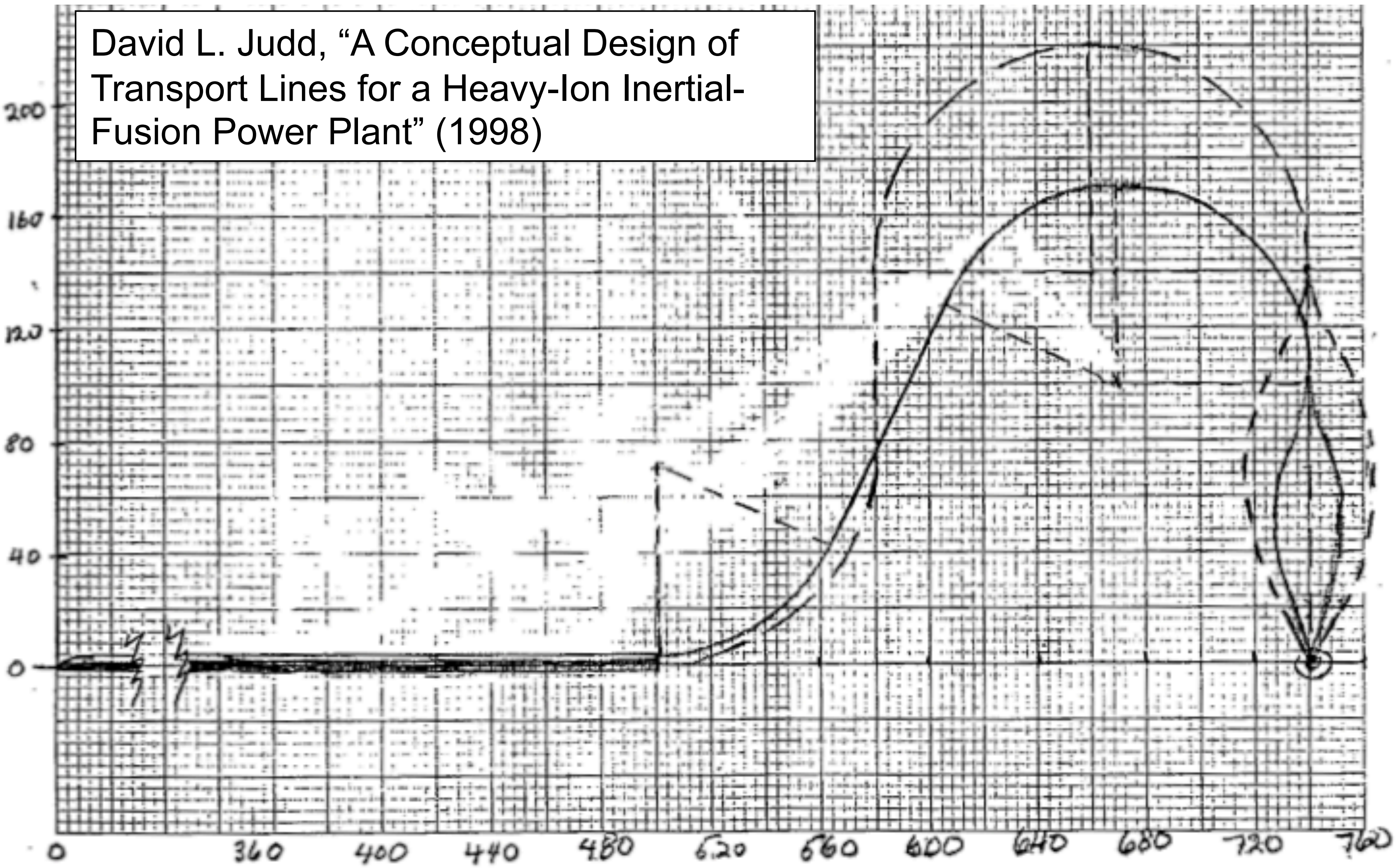
- In the final section of the driver, the beams are separated so that they may converge onto the target in an appropriate pattern.
- They also undergo non-neutral drift-compression, and ultimately "stagnate" to nearly-uniform energy, and pass through the final focusing optic.
- In the scenario examined by Dave Judd (1998), the arcs are ~ 600 m long, while the drift distance should be < 240 m.



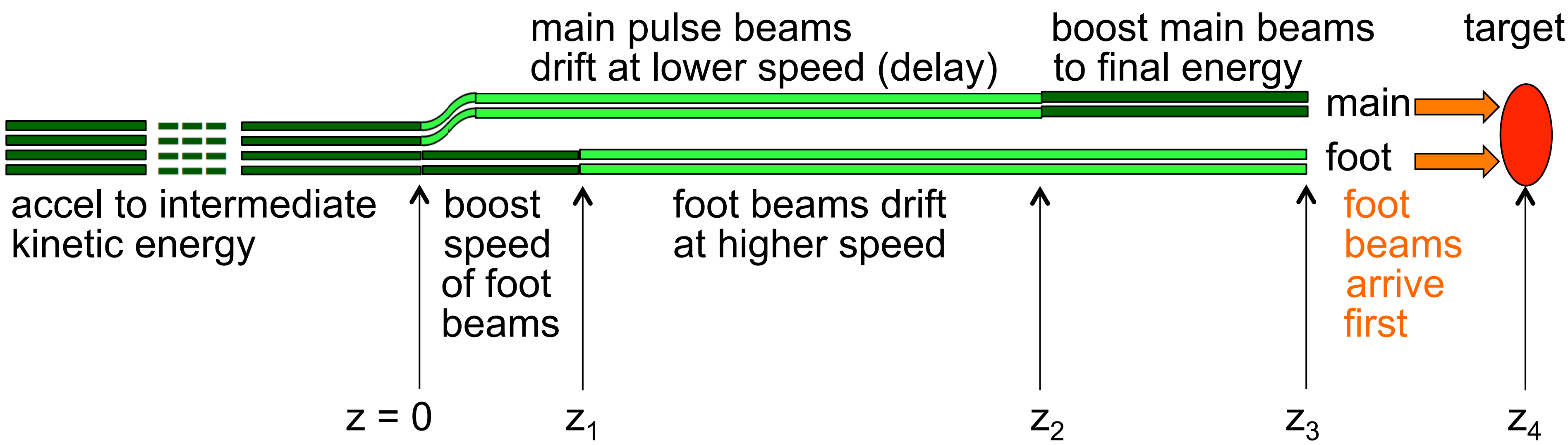

- Thus, the velocity "tilt" must be imposed in the arcs, or upon exit from the arcs.
- To maintain a quiescent beam, "ear fields" are needed in the arcs.
- For pulse-shaping, the arcs may represent an opportunity to pre-configure the beams before final compression.

# If a foot pulse of lower K.E. is needed, those beams are "traditionally" extracted from the linac early and routed via shorter arcs

David L. Judd, "A Conceptual Design of Transport Lines for a Heavy-Ion Inertial-Fusion Power Plant" (1998)



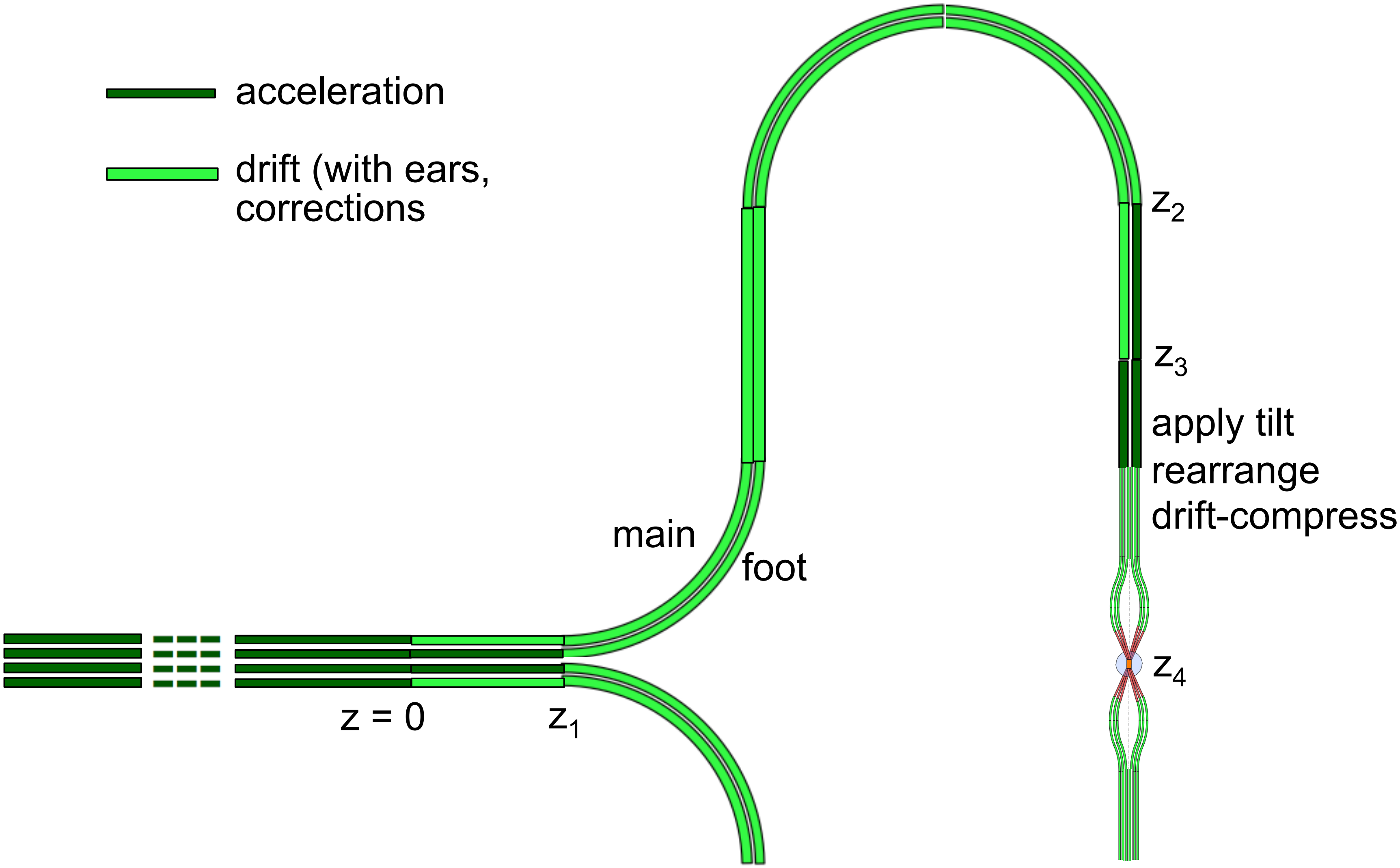
# Delay between foot and main pulses can be inserted in a nearly linear system



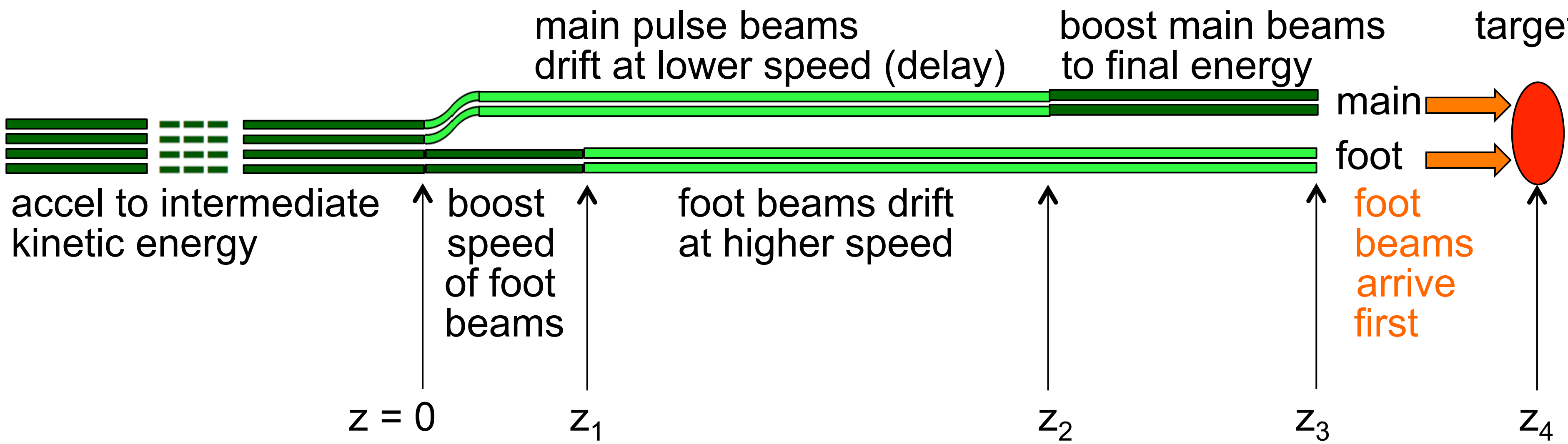

This concept may be useful …

- if two linacs are used, one from each side
- with a single linac, for a single-sided target
- with a single linac, for a two-sided target (see next slide)

# A single linac with common arcs could drive a 2-sided target



# Example: for an indirect-drive target requiring two beam energies




Aion = 208.980 amu

Accelgradient = 3.0 MV/m

Int. Vz = 48.046 m/us, beta = 0.1603

Foot Vz = 52.632 m/us, beta = 0.1756

Main Vz = 60.774 m/us, beta = 0.2027

Int. Ek = 2.5 GeV

Foot Ek = 3.0 GeV

Main Ek = 4.0 GeV

z1 = 0.167 km

z2 = 0.542 km

z3 = 1.042 km

z4 = 1.242 km

t1foot = 3310.884 ns

t1main = 3468.888 ns

t2foot = 10435.840 ns

t2main = 11273.886 ns

t3foot = 19935.780 ns

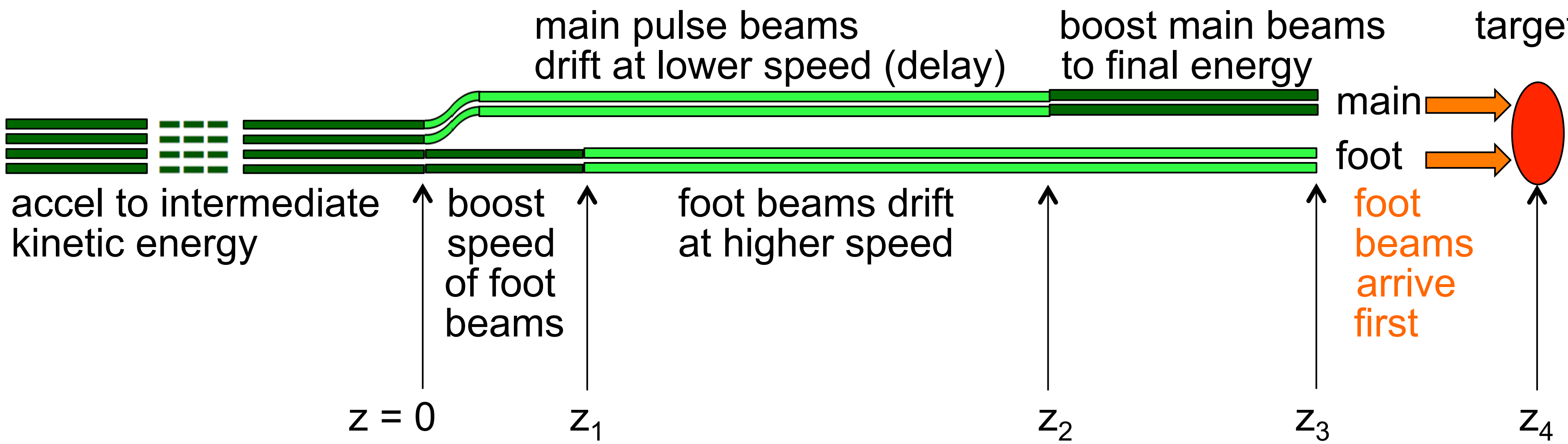
t3main = 20463.353 ns

t4foot = 23735.757 ns

t4main = 23754.229 ns

delay = 18.473 ns

# Example: for an X-target requiring a single beam energy




Aion = 84.910 amu
Accelgradient = 3.0 MV/m
Int. Vz = 165.140 m/us, beta = 0.5509
Foot Vz = 171.883 m/us, beta = 0.5733
Main Vz = 171.883 m/us, beta = 0.5733
Int. Ek = 12.0 GeV
Foot Ek = 13.0 GeV
Main Ek = 13.0 GeV

z1 = 0.333 km
z2 = 0.433 km
z3 = 0.767 km
z4 = 1.067 km

t1foot = 1978.104 ns
t1main = 2018.490 ns
t2foot = 2559.895 ns
t2main = 2624.038 ns
t3foot = 4499.198 ns
t3main = 4602.142 ns
t4foot = 6244.571 ns
t4main = 6347.515 ns
delay = 102.944 ns

# 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

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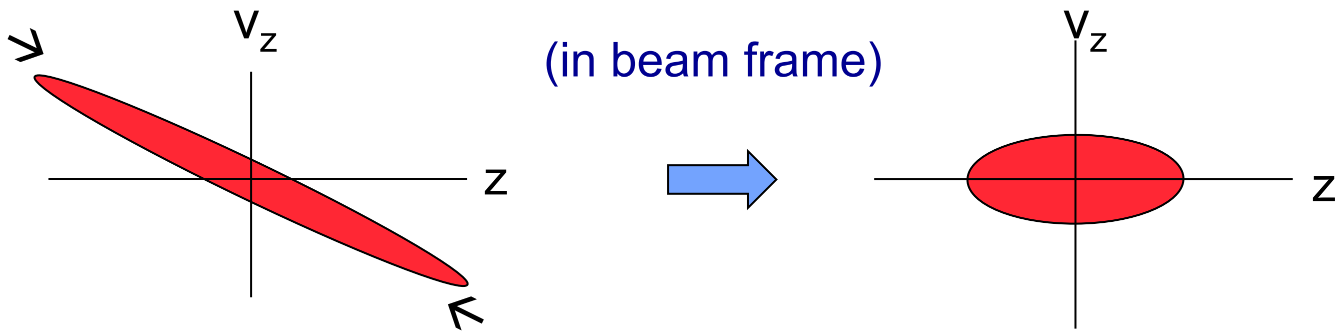
- In non-neutral drift compression, the space charge force opposes ("stagnates") the inward flow, leading to a nearly mono-energetic compressed pulse:

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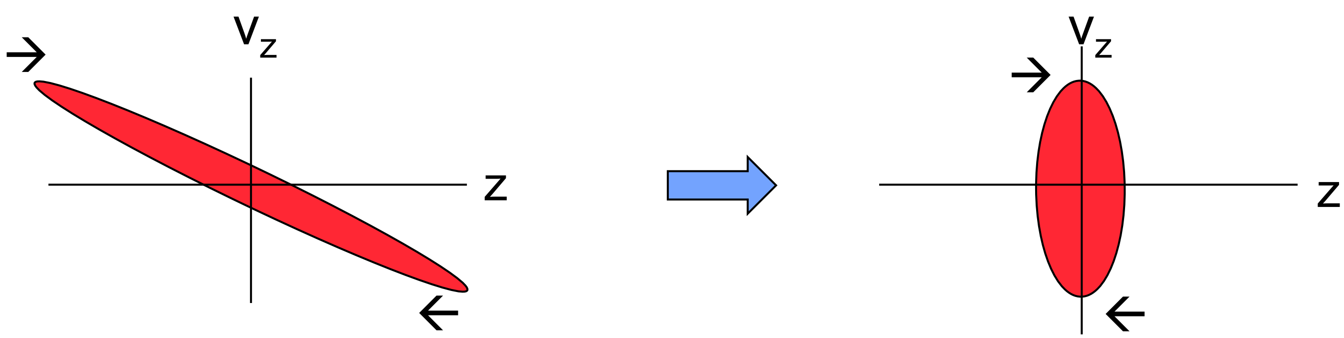
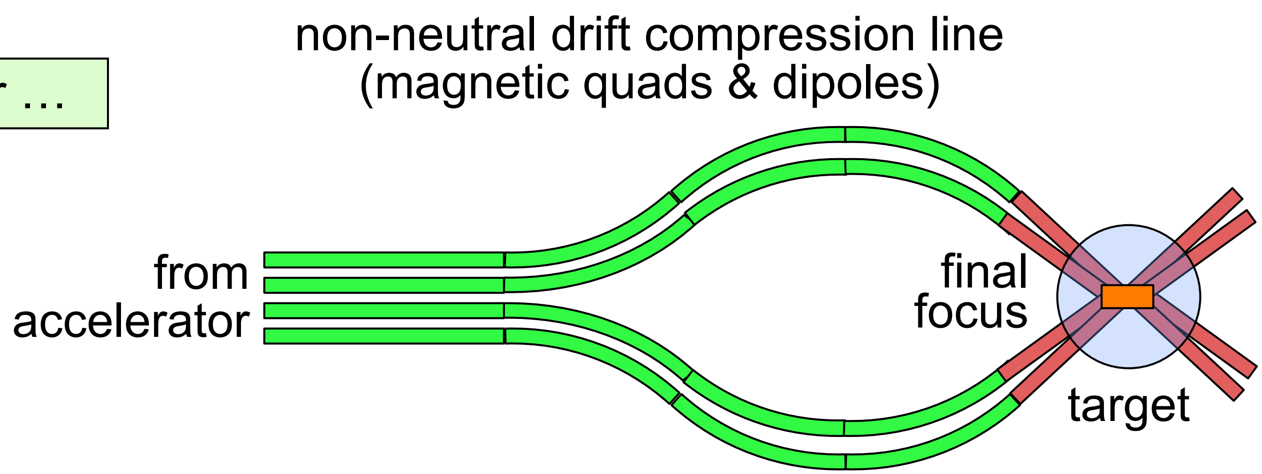
- In neutralized drift compression, the space charge force is eliminated, resulting in a shorter pulse but a larger velocity spread:

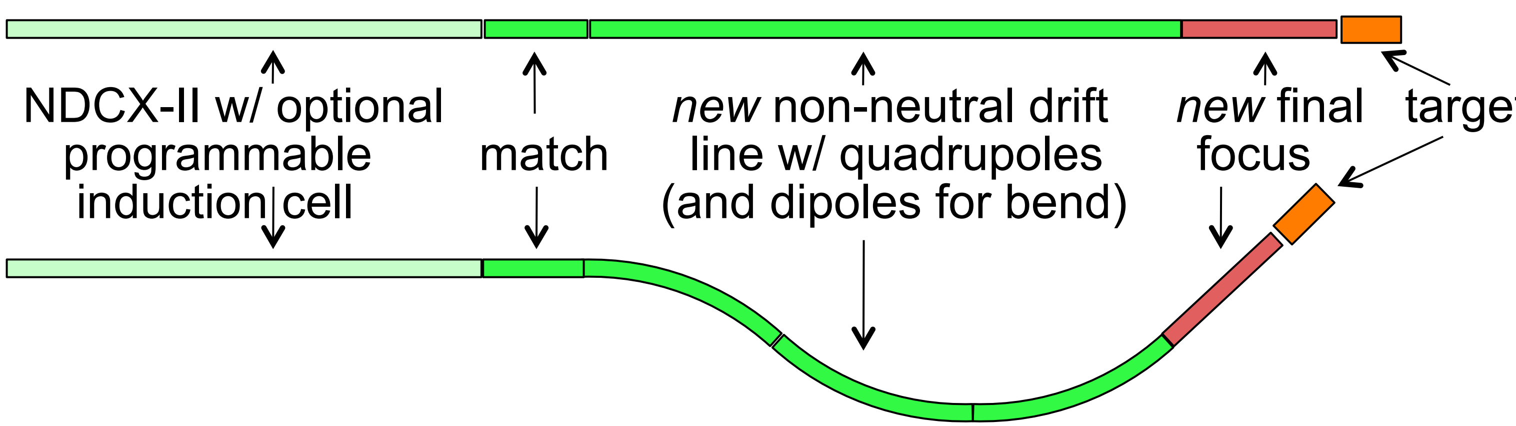


# Experiments on NDCX-II can explore non-neutral compression, bending, and focusing of beams in driver-like geometry

In a driver …



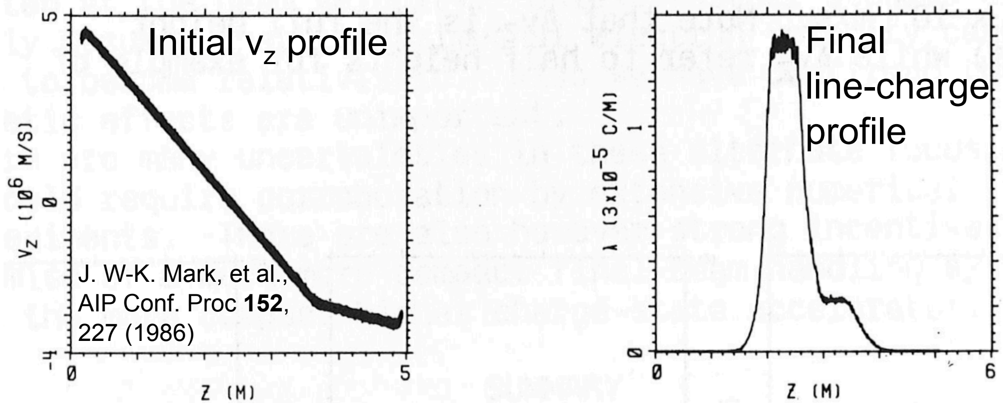

On NDCX-II, two configurations to test …



# HIF-motivated 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.