Realistic Simulation of NDCX II*

W M Sharp, A Friedman, D P Grote, R H Cohen - *LLNL*
E Henestroza, M A Leitner, W L Waldron, L L Reginato, J-L Vay - *LBNL*

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Heavy Ion Fusion Science
Virtual National Laboratory

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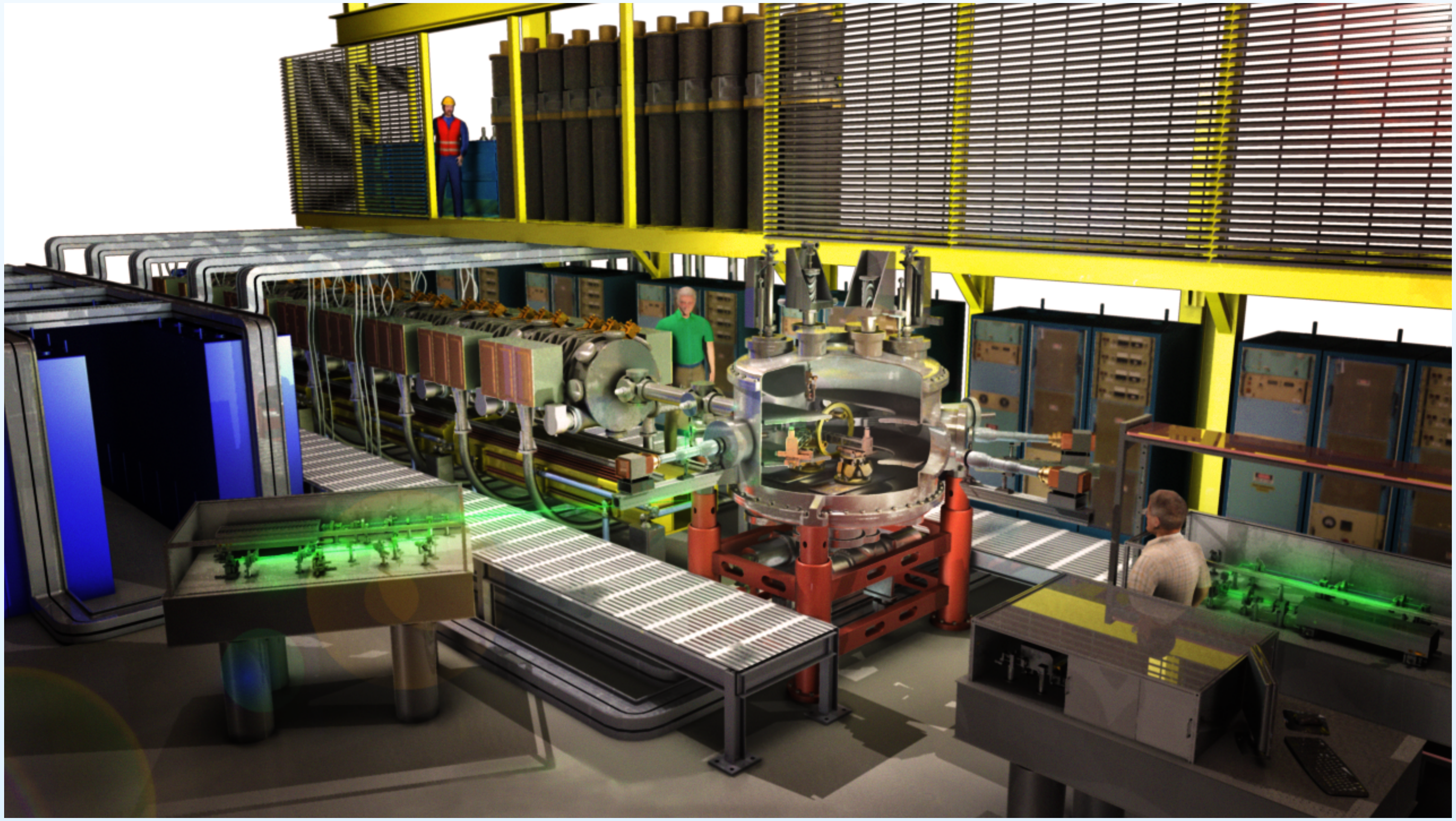
Construction of NDCX-II is underway at LBNL

NDCX-II is a successor to the Neutralized Drift-Compression eXperiment (NDCX-I)

- designed to study warm dense matter and the physics of fusion targets heated by ions
- built largely of hardware from the decommissioned LLNL Advanced Test Accelerator
- WDM target requirements are stringent

  for Li+ we need 30-50 nC at 1.2 - 3 MeV

  beam must be compressed to a 1-cm length (~1 ns) and a sub-mm diameter



The NDCX II physics design is tightly constrained

design goals

- meet NDCX-II experimental requirements energy, spot size, and duration
- avoid expensive pulsers by keeping waveforms simple
- minimize cost by using as much ATA hardware as possible

hardware options are limited by reuse of existing components

- use of ATA cells sets cell period, gap size, and beam-pipe aperture
- ferrite cores are limited to 0.014 V-sec (200 kV for 70 ns)
- number of cells should not exceed about 40 due to space and funding limits
- spaces without cells or solenoids are needed for diagnostics and pumping
- any space between cells should be integral number of ATA periods

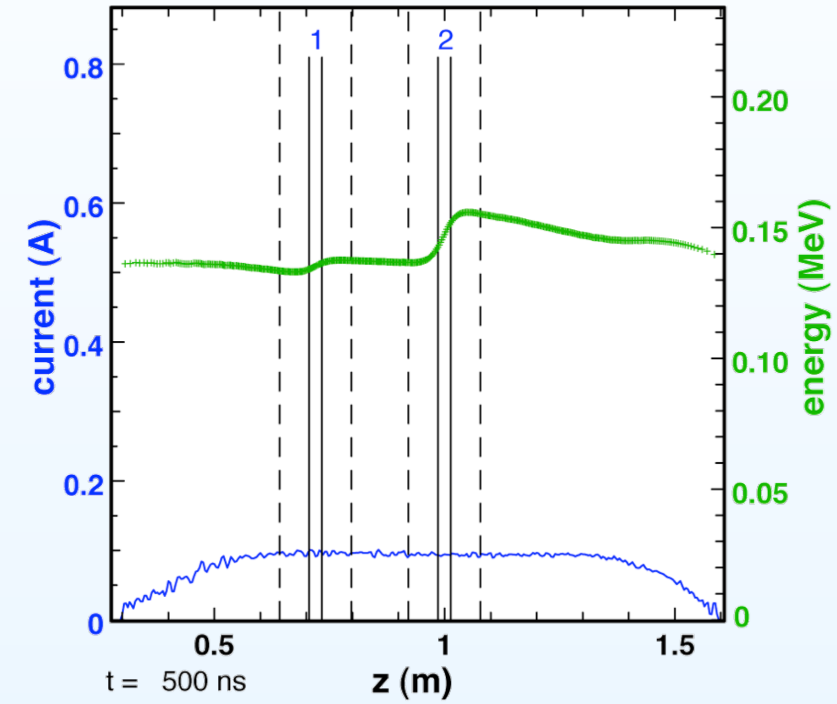
waveforms must reflect engineering and physics limits

- unaltered ATA pulsed-power modules produce flat-topped pulses
- simple modifications can produce trapezoidal waveforms and other basic shapes
- more elaborate waveforms would require *very* expensive pulsers
- breakdown limits maximum voltage to 250 kV
- 6.7-cm ATA beam-pipe radius must be reduced to 4 cm in NDCX-II
  - original radius gives gap fringe fields that nearly fill the 28-cm cell period
  - resulting gap-transit times would have compromised the voltage gain per cell

Several tools are used to develop a physics design

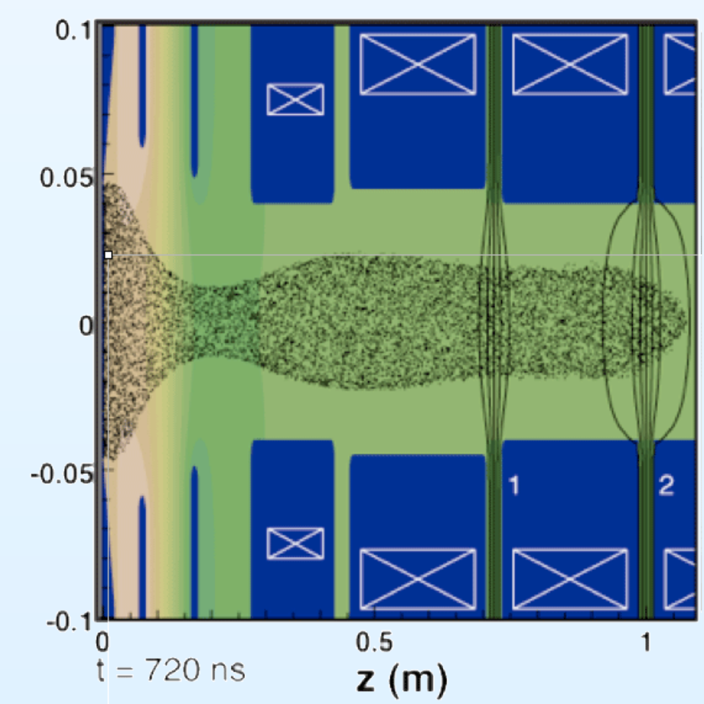
1-D Acceleration Schedule Program simulations

- fast-running particle simulation
- developed for NDCX-II design work
- initialization from Warp injection data
- 1-D space-charge representation from HINJ
- realistic on-axis gap fringe fields
- respects volt-seconds and voltage constraints
- waveform optimization
- centroid equations



r-z Warp simulations

- needed to validate 1-D code and to model radial physics
  - transverse matching and final focus
  - growth of transverse emittance
  - radial variations in space-charge force and gap fringe fields
- imports lattice and waveforms are imported from ASP
- generates beam ions from realistically modeled injector
- solenoid model includes copper flux return



3-D Warp simulations

- needed to set tolerances for alignment and for waveform accuracy and timing

1-D simulations

ASP is used to develop acceleration schedule

NDCX-II strategy is to compress quickly than accelerate

- makes best use of available volt-seconds
- requires only simple waveforms
- avoids the need for longitudinal-control waveforms after initial energy adjustment
  - compressed beam lengthens due to space charge
  - acceleration is chosen to keep beam duration less than 70-ns

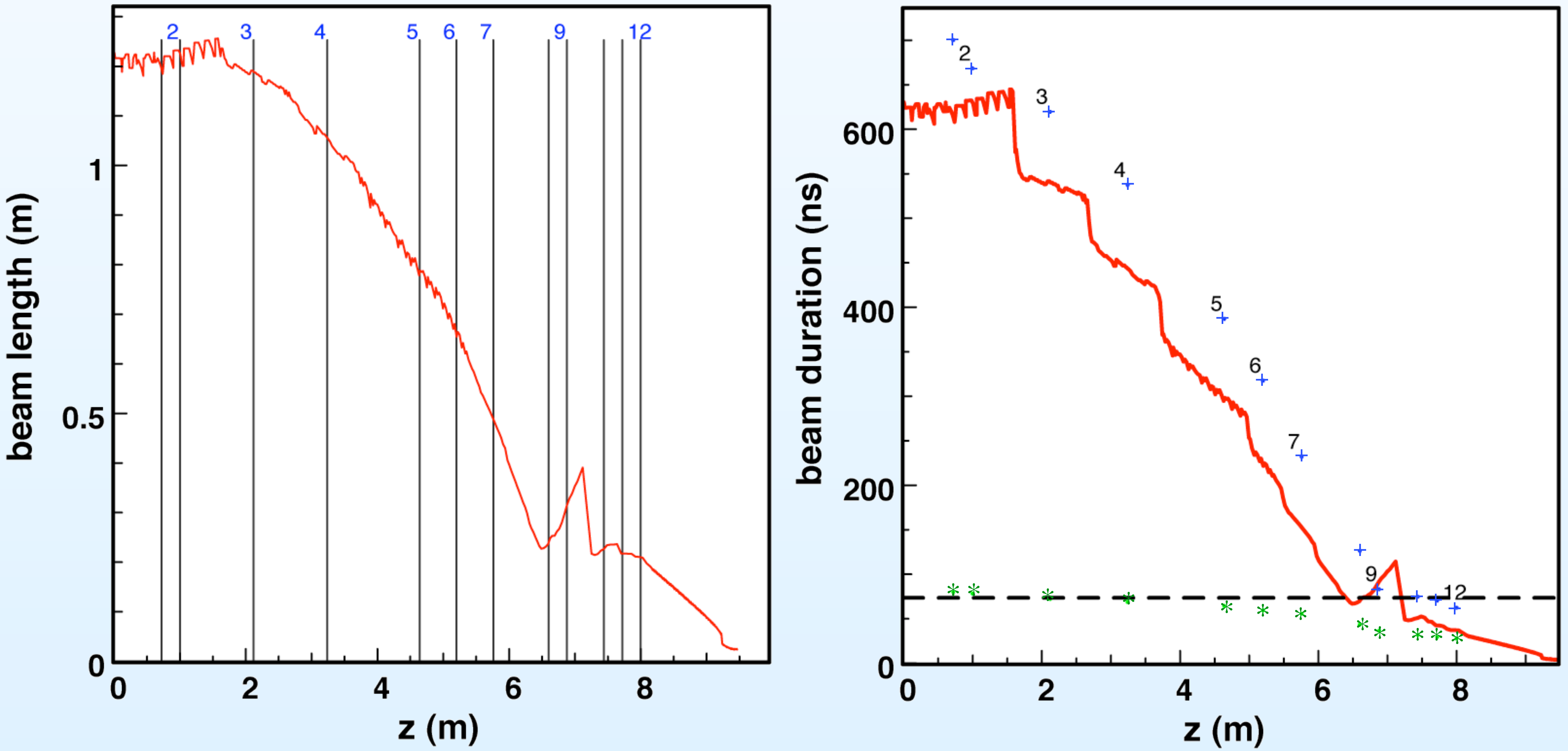
acceleration schedule is developed by mix of optimization and user intuition

- acceleration lattice is built from standard parts
  - every element uses the 28-cm ATA period
  - all cells use ATA ferrite cores and have 2.8-cm gap
  - beam-pipe radius is 4 cm in all elements
- ASP user specifies sequence of lattice elements
- velocity tilt is specified by choosing analytic parameters or experimental waveforms
- groups of gaps are optimized to improve beam linearity and uniformity

Novel acceleration schedule makes effective use of ATA parts

rapid non-neutral compression to 70-ns duration maximizes use of ATA Blumleins

- apply head-to-tail velocity "tilt" with waveforms chosen to optimize linearity of v_z vs z
- space charge limits compression and causes beam to "bounce"
- apply triangular or trapezoidal waveforms to keep beam duration less than 70 ns
- apply triangular waveforms in final cell block to produce final velocity tilt



The ASP model has progressively become more predictive

first version (November 2007)

- ideal initial flat-topped pulse with quadratic current rise and fall
- idealized waveforms
- g-factor model of beam space charge
- hard-edged gap fields

2008

- additional initialization parameters to model current and energy variation at beam ends
- HINJ model for beam space charge
- circuit model and additional waveforms added as options
- Lee model of gap fringe fields

2009

- name for code
- initialization from Warp injector simulations
- optional use of experimental waveforms with timing optimization
- centroid equations to model effects of solenoid misalignments and test steering algorithms

2010

- optional use of experimental waveforms with optimized scaling,timing, and voltage offset
- extensive revision of code to improve optimization and communication with Warp

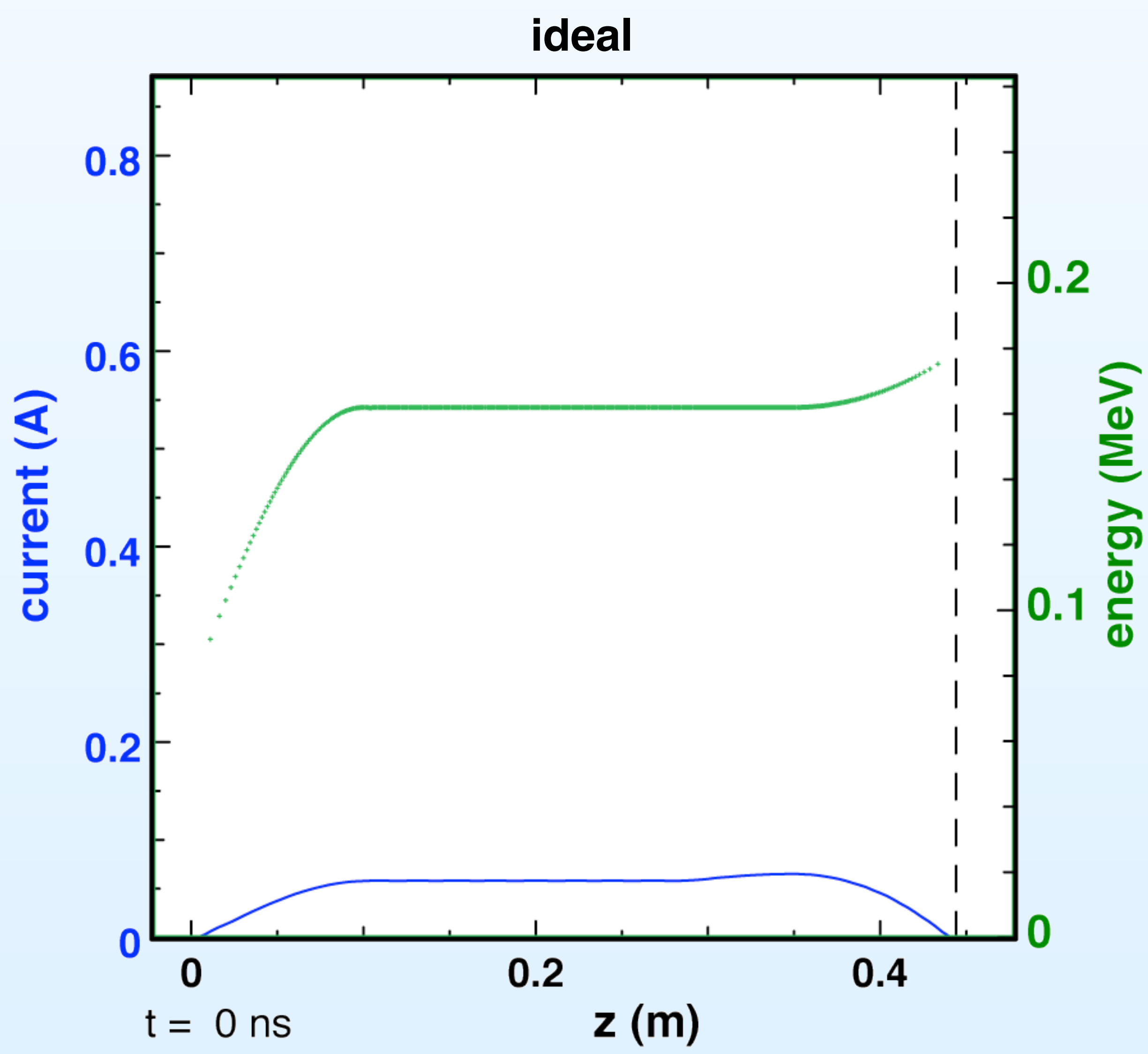
ASP beams are now initialized from Warp injector runs

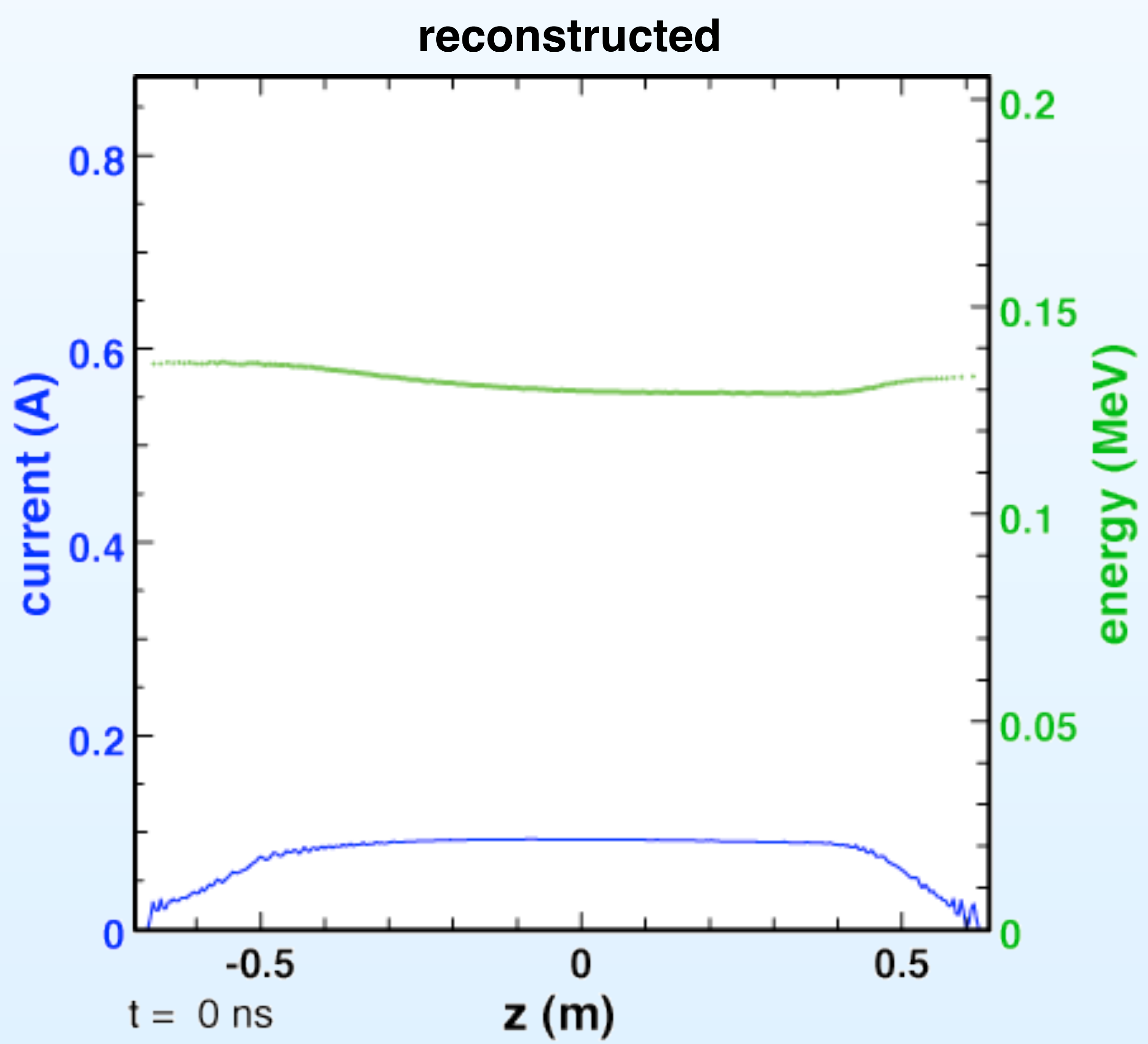
early ASP runs used ideal current and energy variations

- user specified parameters controlling length, current, and energy of head, body, and tail
- differences from Warp initialization frustrated comparisons between codes

recent runs construct initial beam from Warp data captured just after injector

- improved injector design reduced earlier energy variation near ends



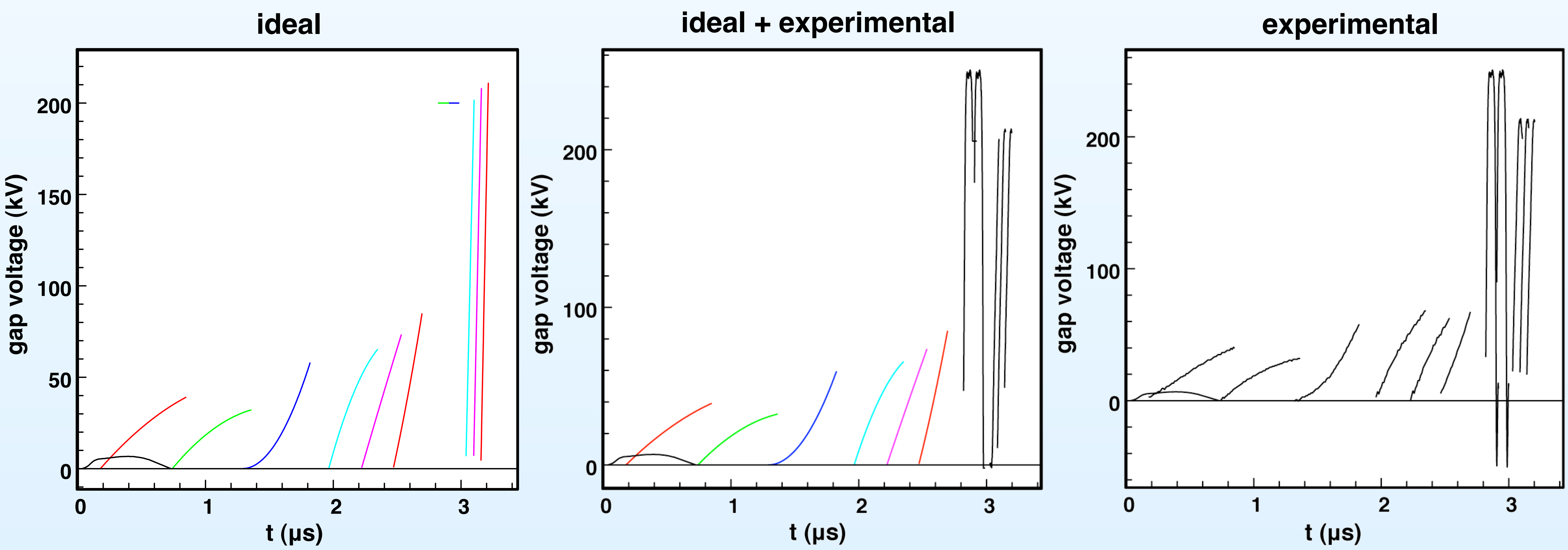


ASP now uses experimental waveforms rather than ideal ones

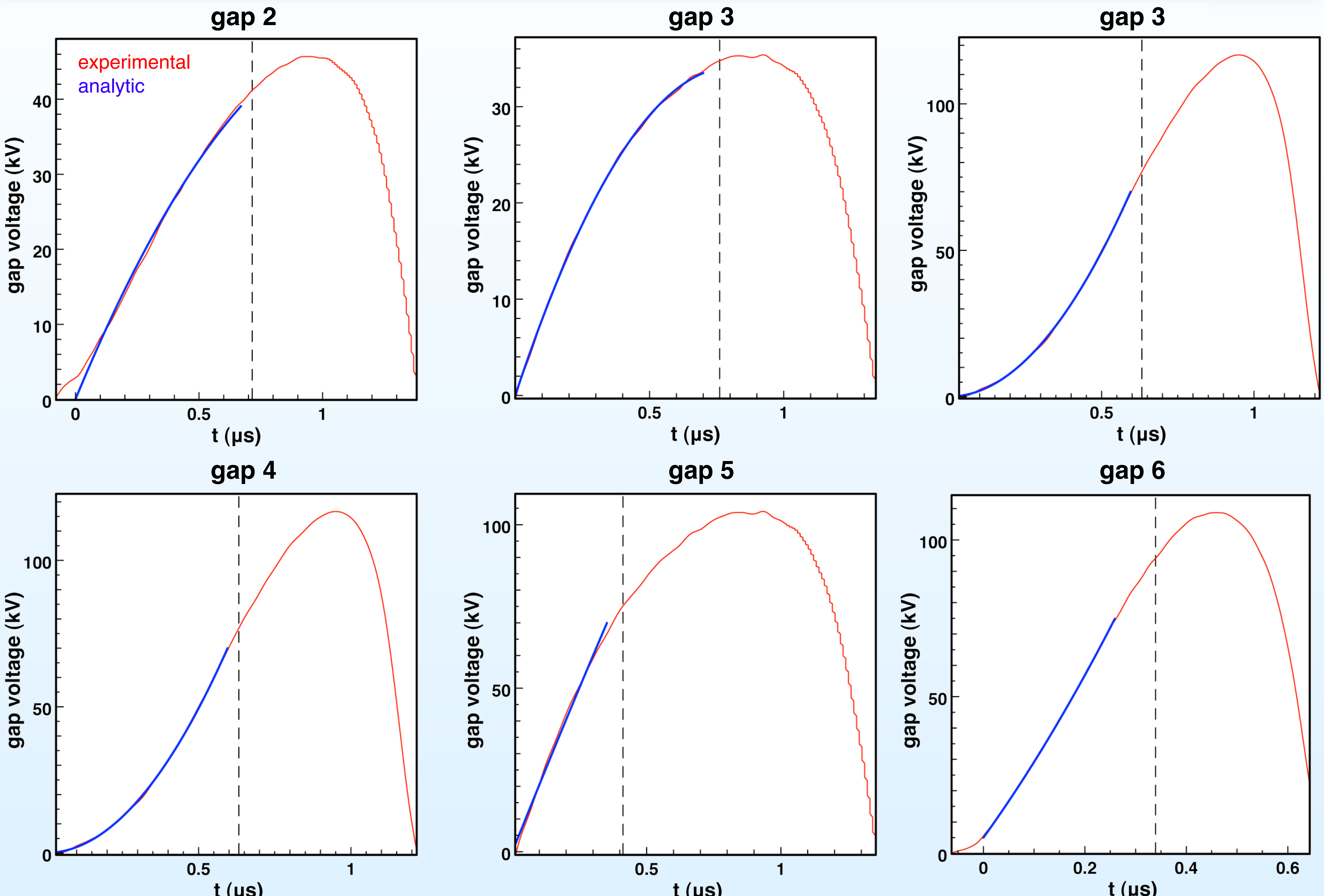
nearly all waveforms in are simple

- first cell corrects energy variation from injector
- six widely spaced “compresssion” cells impose tilt with optimized waveforms
- flat-topped “acceleration” pulses in following cells allow beam to bounce
- final “tilt” cells use ramped waveforms to impose head-to-tail velocity variation

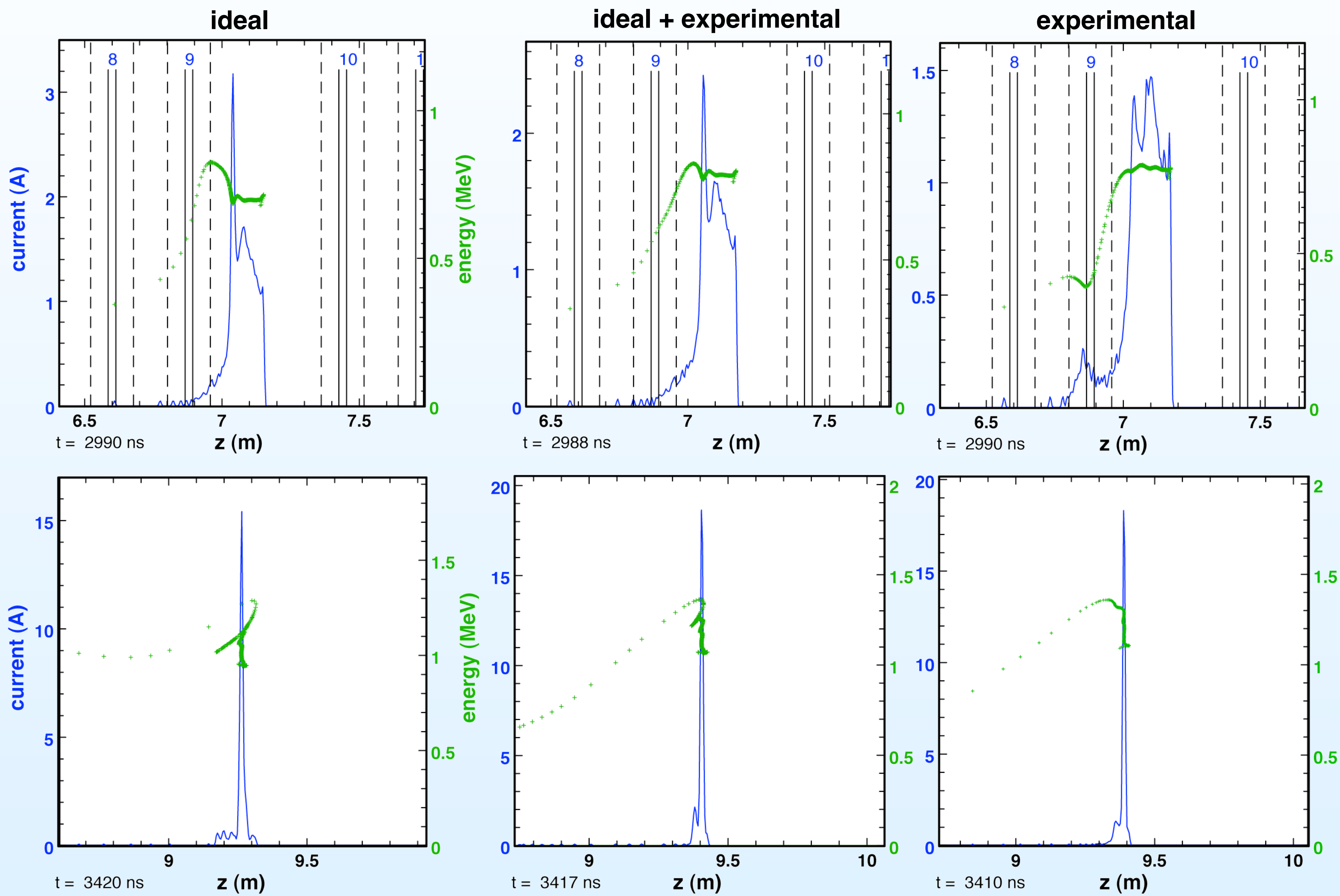
optimization is used to match experimental waveforms to idealized ones



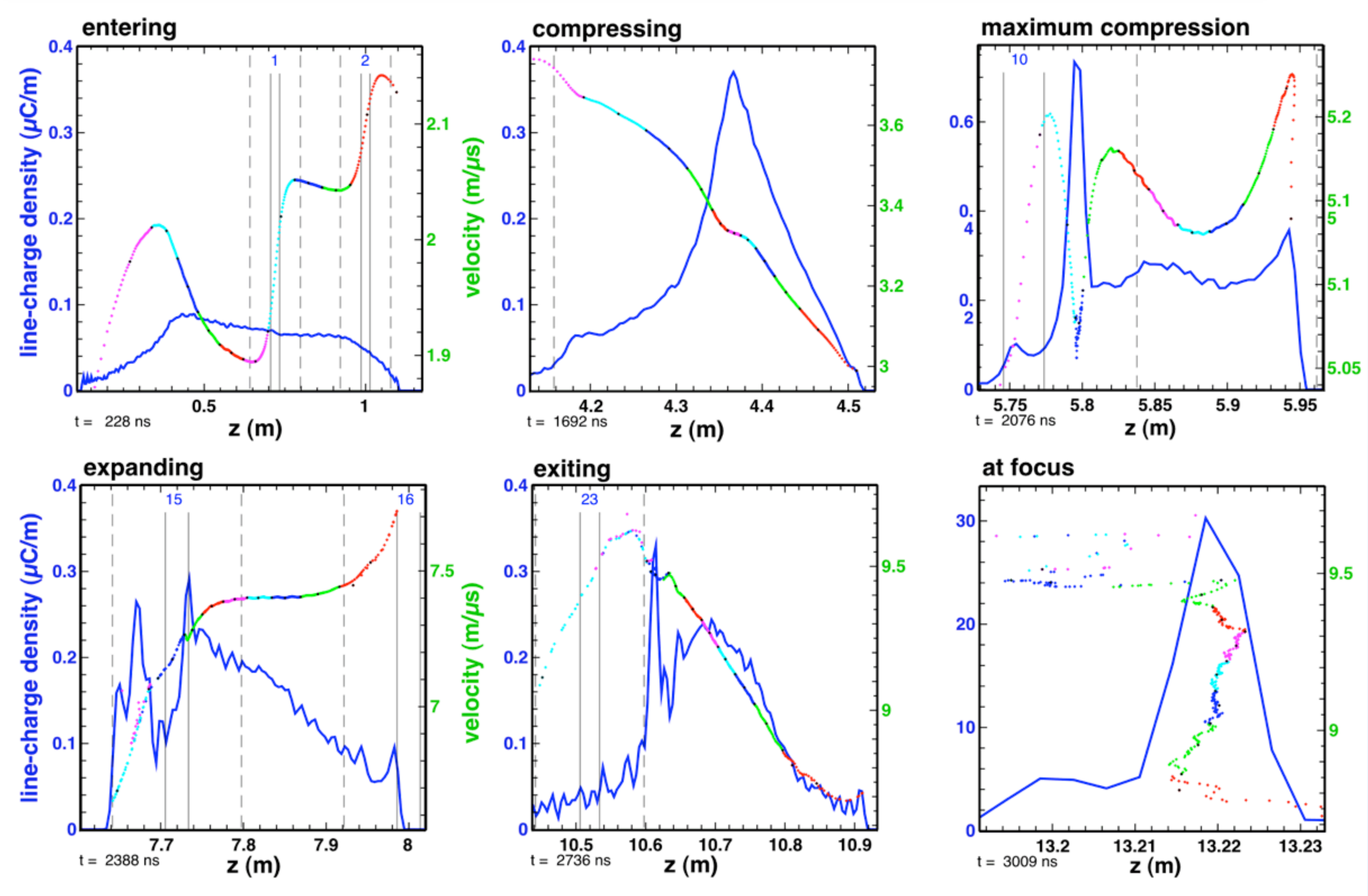
Experimental waveforms can be tailored to match analytic ones



Experimental waveforms yield better results due to optimization

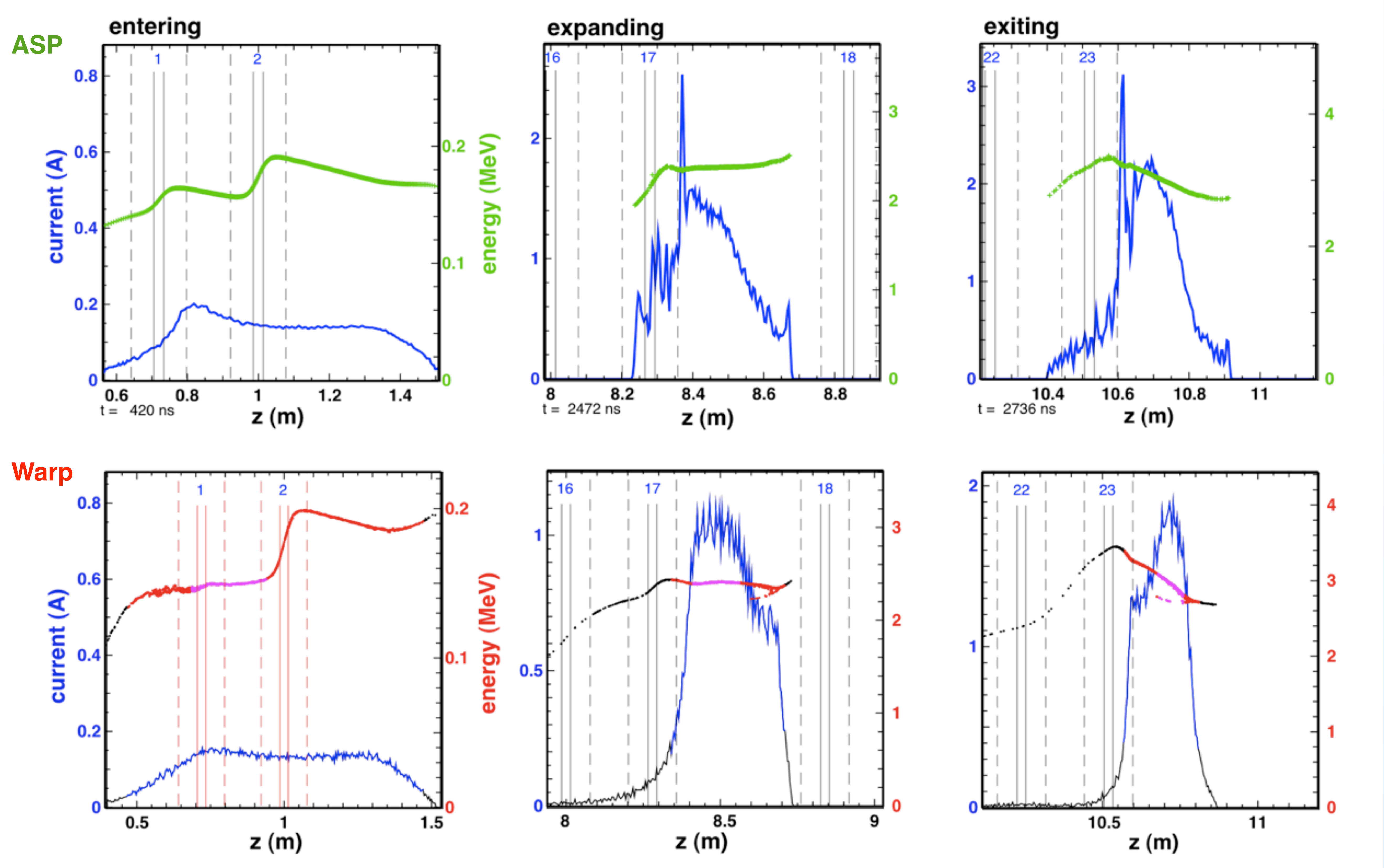


Particle mixing occurs largely at beam ends

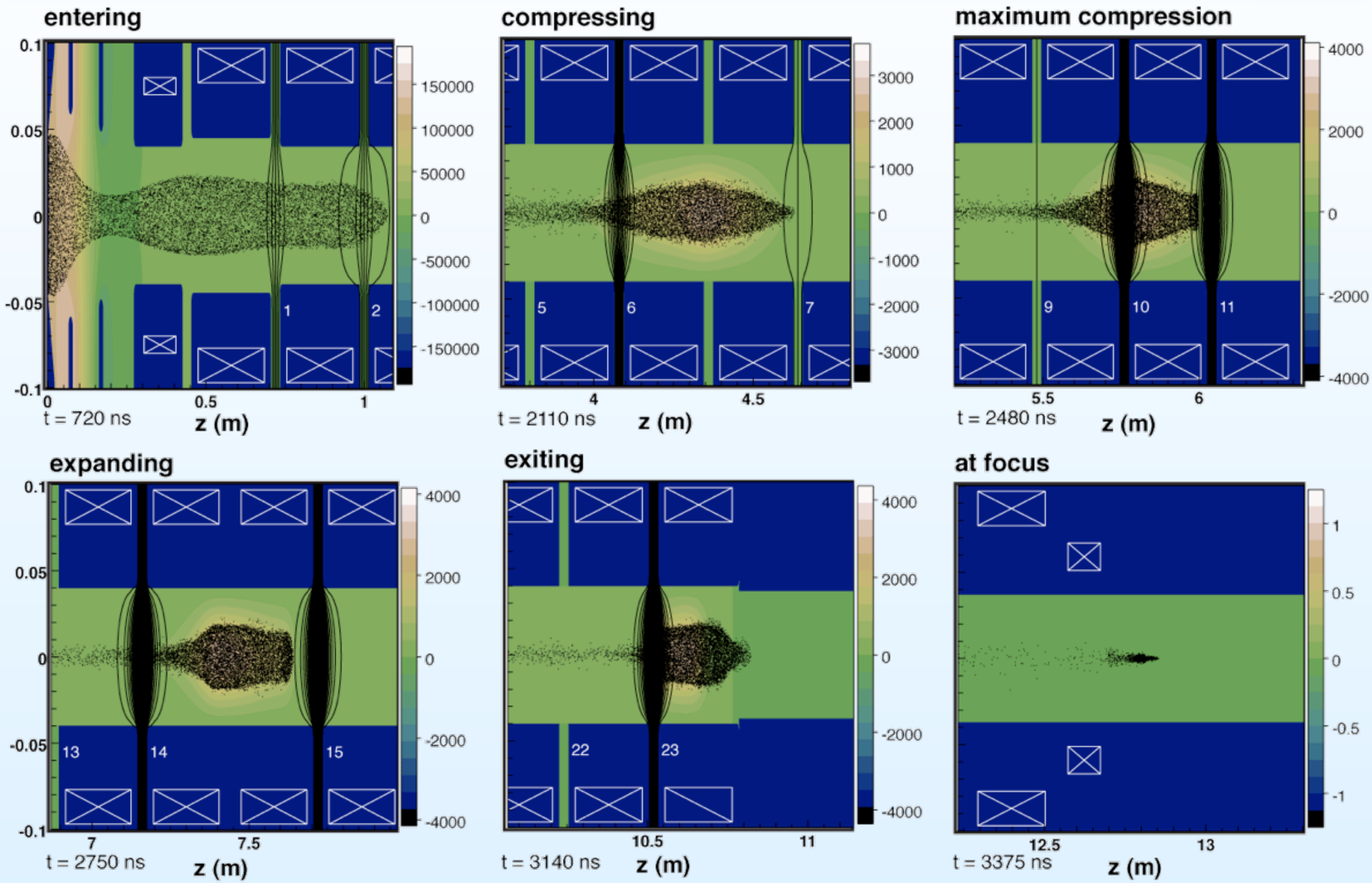


Warp *r-z* simulations

Beam dynamics in ASP compare well with Warp



Warp shows good radial and longitudinal beam confinement

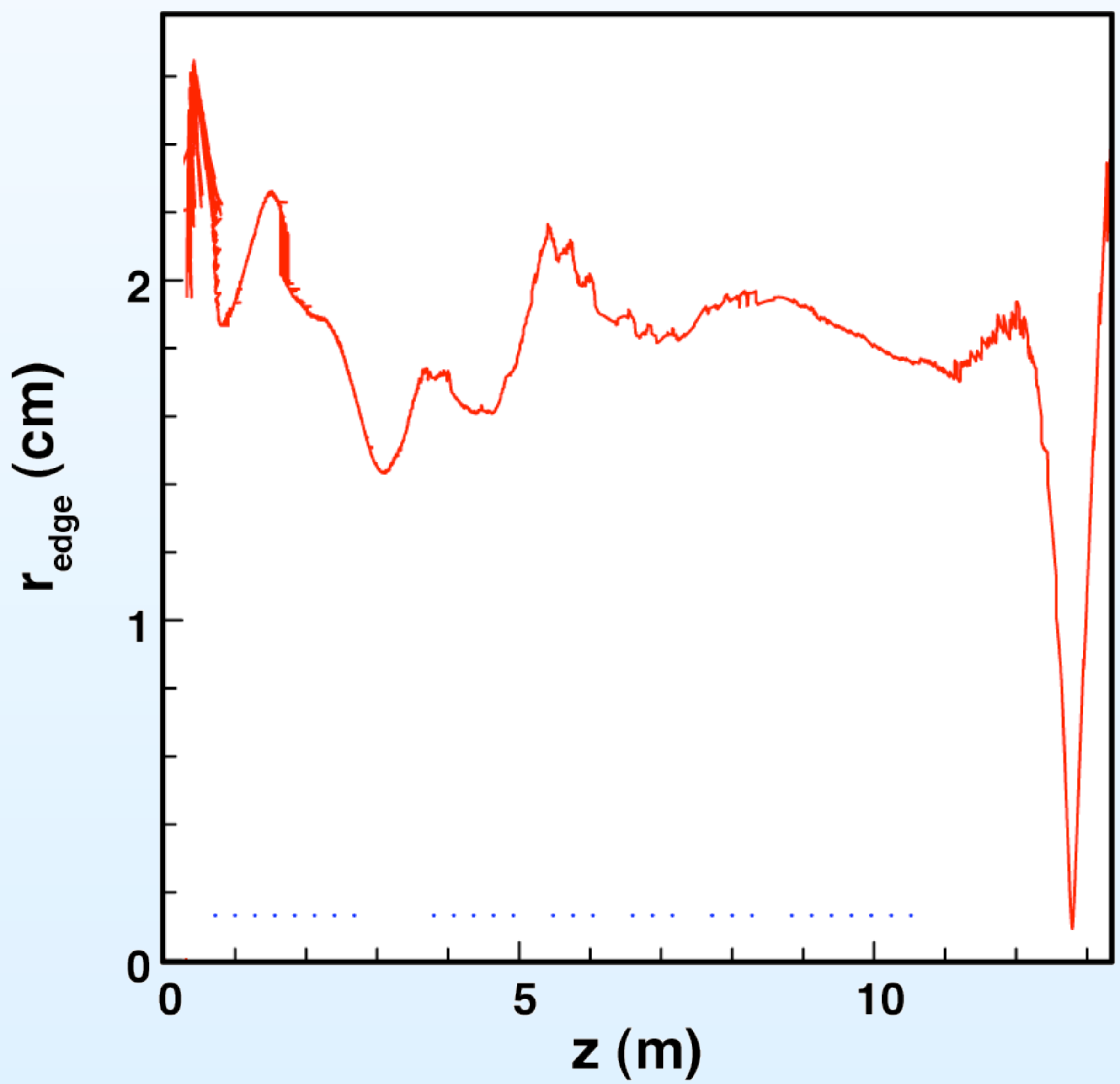


Requirements for transverse confinement appear manageable

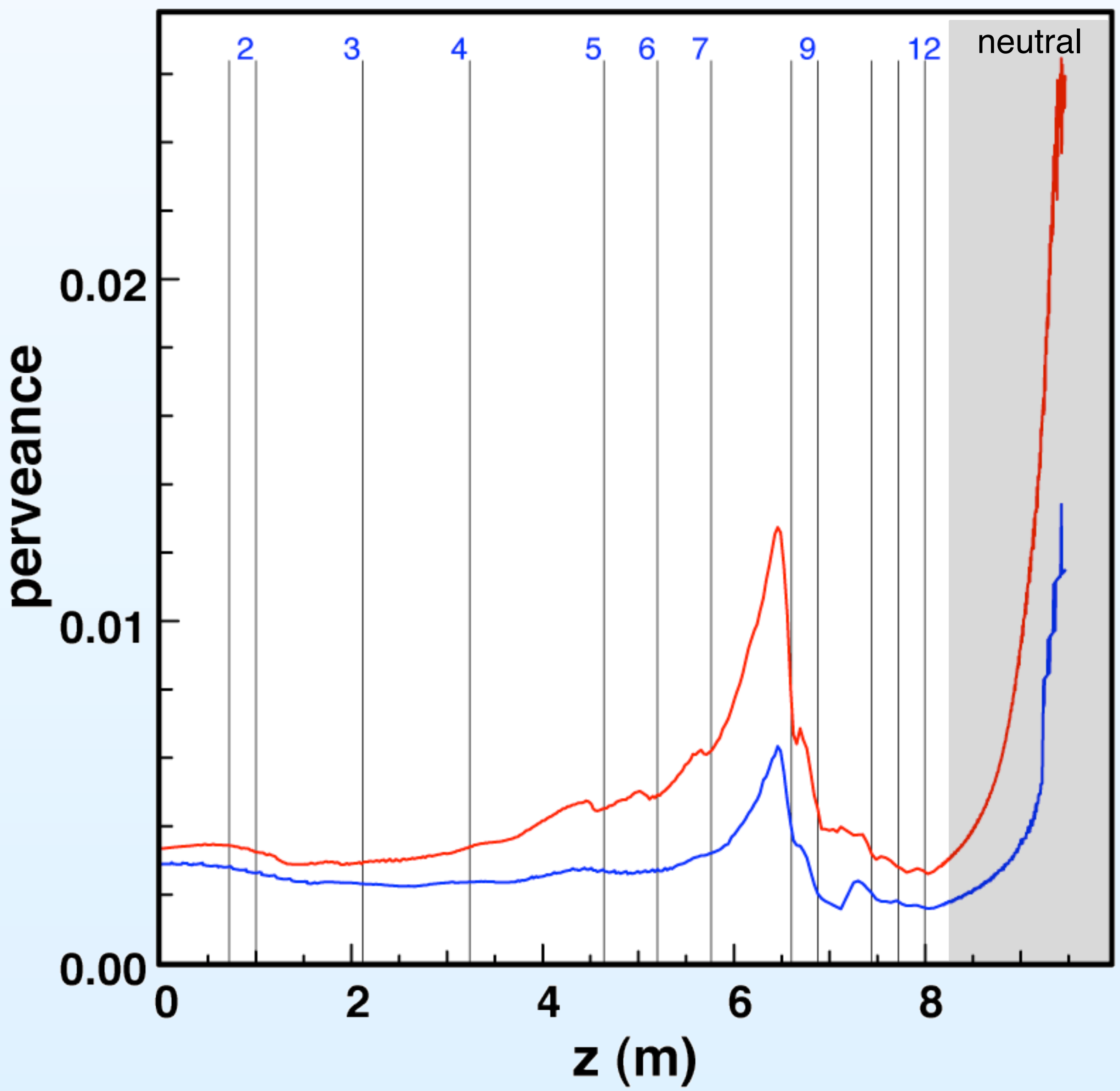
solenoids with strengths of 2 T or less confine beam radius to about 2 cm

- with hand tuning, beam radius remains near 2.3 cm through acceleration lattice
- 8-T final-focus solenoid gives 0.7-mm rms spot radius
- beam perveance becomes extraordinarily large near points of maximum compression

edge radius



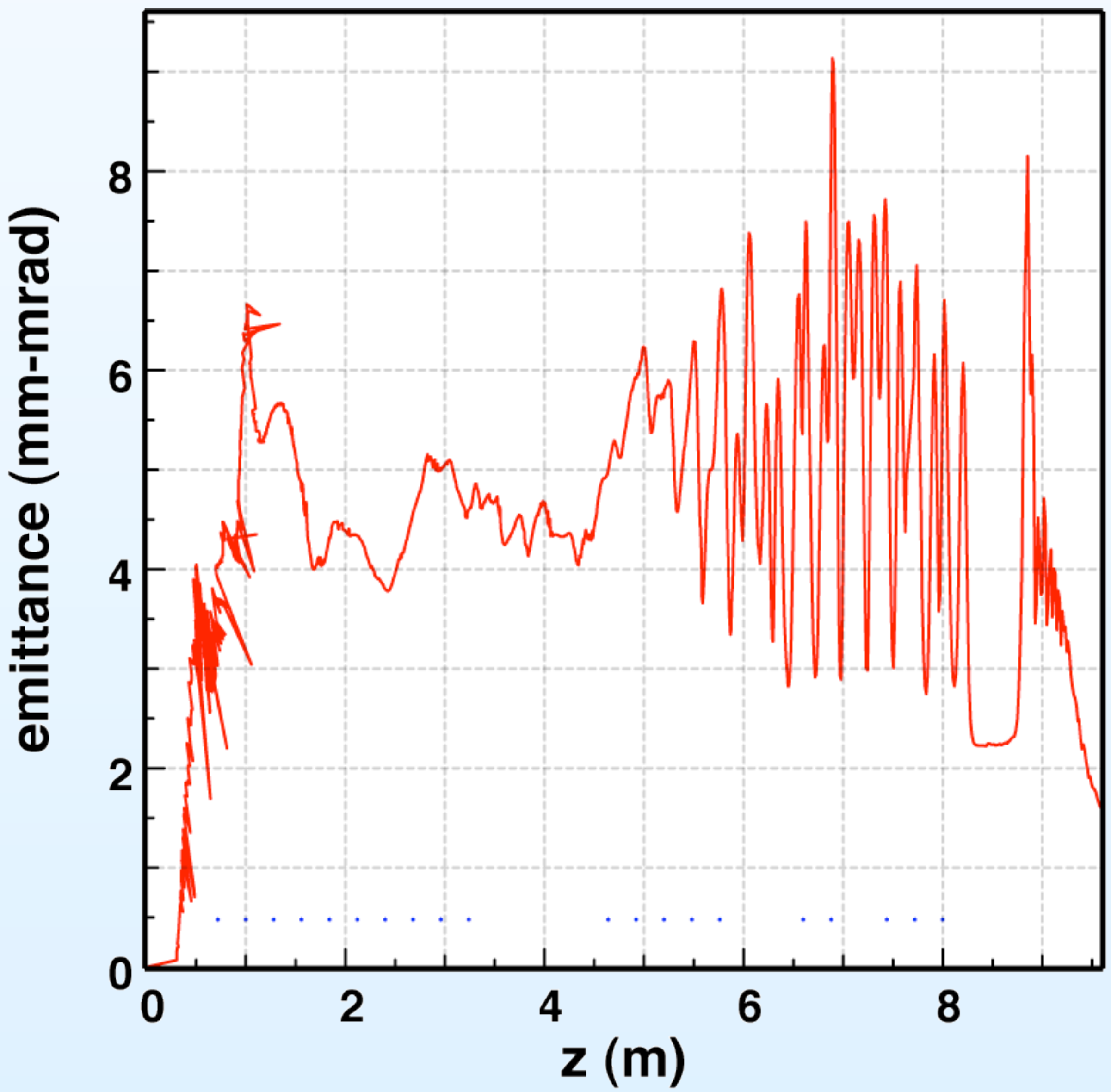
perveance $\kappa = (2\pi\varepsilon_0)^{-1} q e I_b / M_b v_z^2$



Emittance growth during acceleration appears negligible

r-r´ emittance shows no secular growth during acceleration

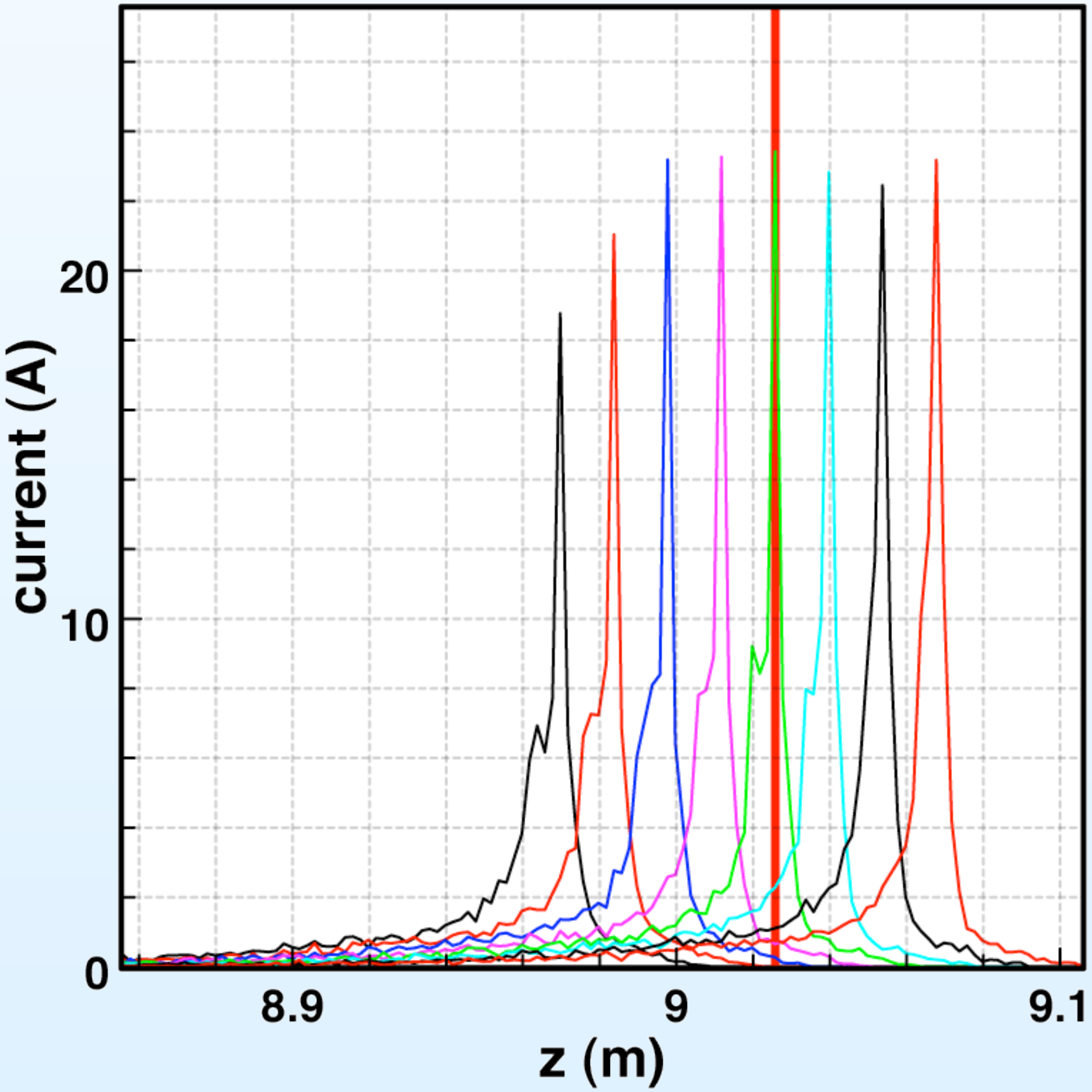
- fluctuations appear correlated with radial oscillations
- solenoids errors are not included in this calculation
- emittance growth remains small enough for adequate final compression

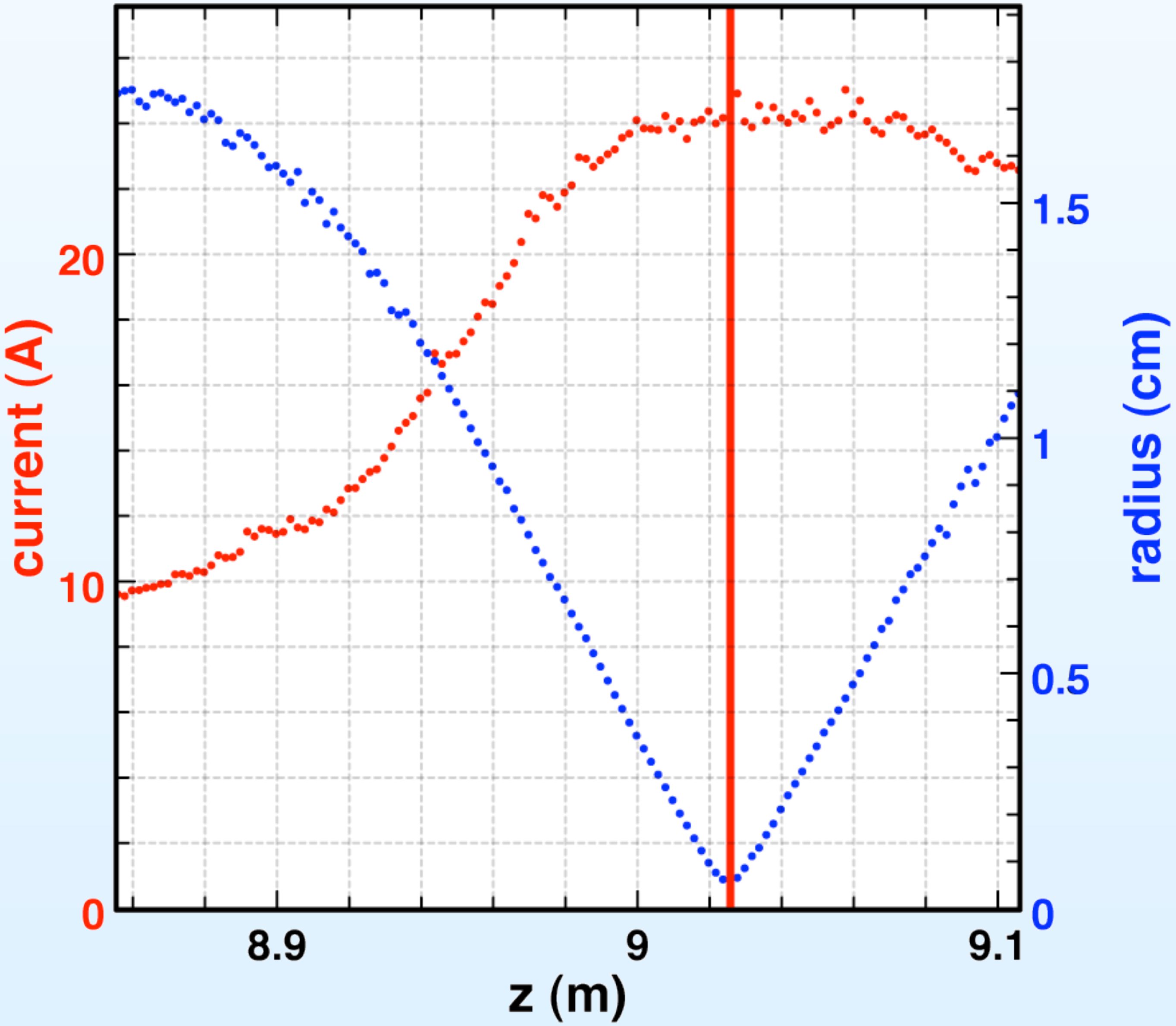


How well-focused is the beam?

23-cell case focuses longitudinally and radially near the same z

- longitudinal focus is well-predicted by analytic algorithm
- longitudinal position of final solenoids is set automatically
- region of good focus is about 10 cm longitudinally and 2 cm radially

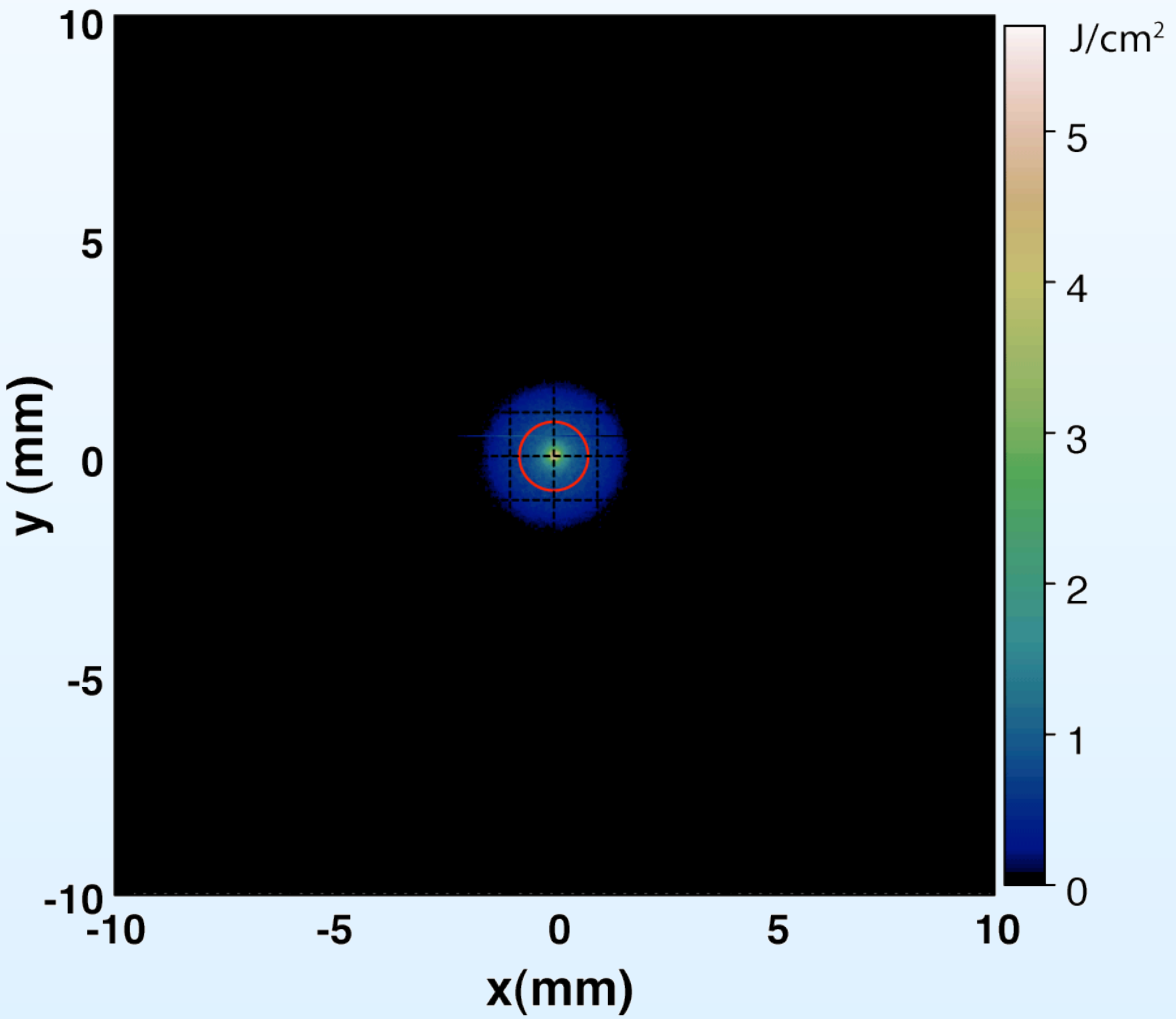




How good is the final focus?

focal spot for 12-cell case gives useful fluence for WDM experiments

- rms radius is about than 0.6 mm for 8-T final-focus solenoid
- most of the energy is deposited within a 1-ns window
- maximum shock wave pressure in Au foil target estimated to be 0.18 Mbar



upgrades can significantly enhance NDCX-II capabilities

	NDCX-I (bunched beam)	NDCX-II construction project			NDCX-II 21-cell
		12-cell (baseline)	15-cell	18-cell	
Ion species	K^+ (A=39)	Li^+ (A=7)	Li^+ (A=7)	Li^+ (A=7)	Li^+ (A=7)
Total charge	15 nC	50 nC	50 nC	50 nC	50 nC
Ion kinetic energy	0.3 MeV	1.2 MeV	1.7 MeV	2.4 MeV	3.1 MeV
Focal radius (50% of beam)	2 mm	0.6 mm	0.6 mm	0.6 mm	0.7 mm
Duration (bi-parabolic measure = √2 FWHM)	2.8 ns	0.9 ns	0.4 ns	0.3 ns	0.4 ns
Peak current	3 A	36 A	73 A	93 A	86 A
Peak fluence (time integrated)	0.03 J/cm^2	13 J/cm^2	19 J/cm^2	14 J/cm^2	22 J/cm^2
Fluence w/in 0.1 mm diameter, w/in duration		8 J/cm^2	11 J/cm^2	10 J/cm^2	17 J/cm^2
focal spot figure of merit		0.18	0.48	0.48	0.64

ASP and Warp *3-D* simulations

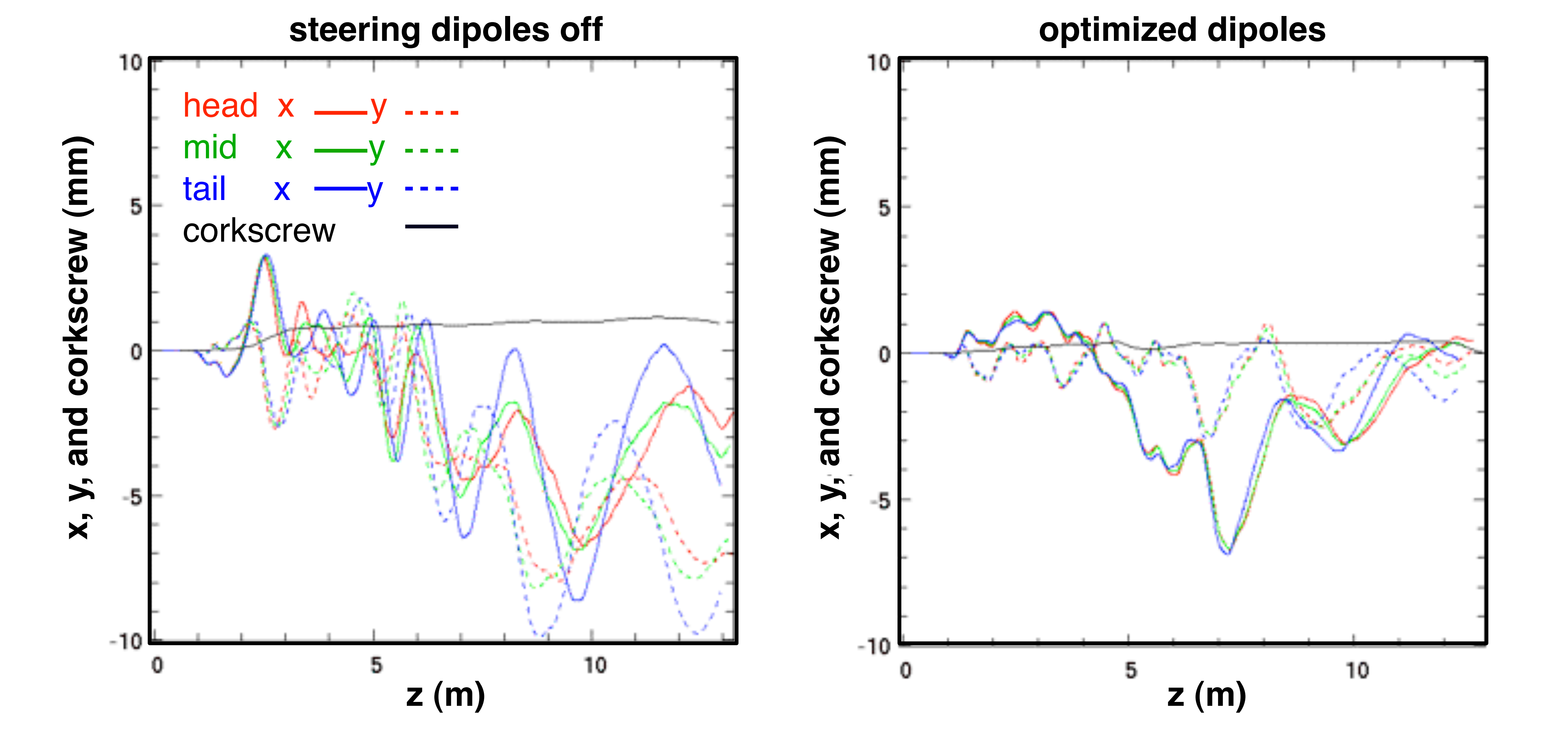
Effects are solenoid alignment errors are being modeled in ASP

ASP runs show solenoid misalignments cause centroid to wander

- random offsets of solenoid ends up to 1 mm were used, and effect scales linearly
- uncorrected errors lead to displacements up to 1 cm plus a 1-mm corkscrew

optimized dipole steering largely eliminate corkscrew and reduce displacement

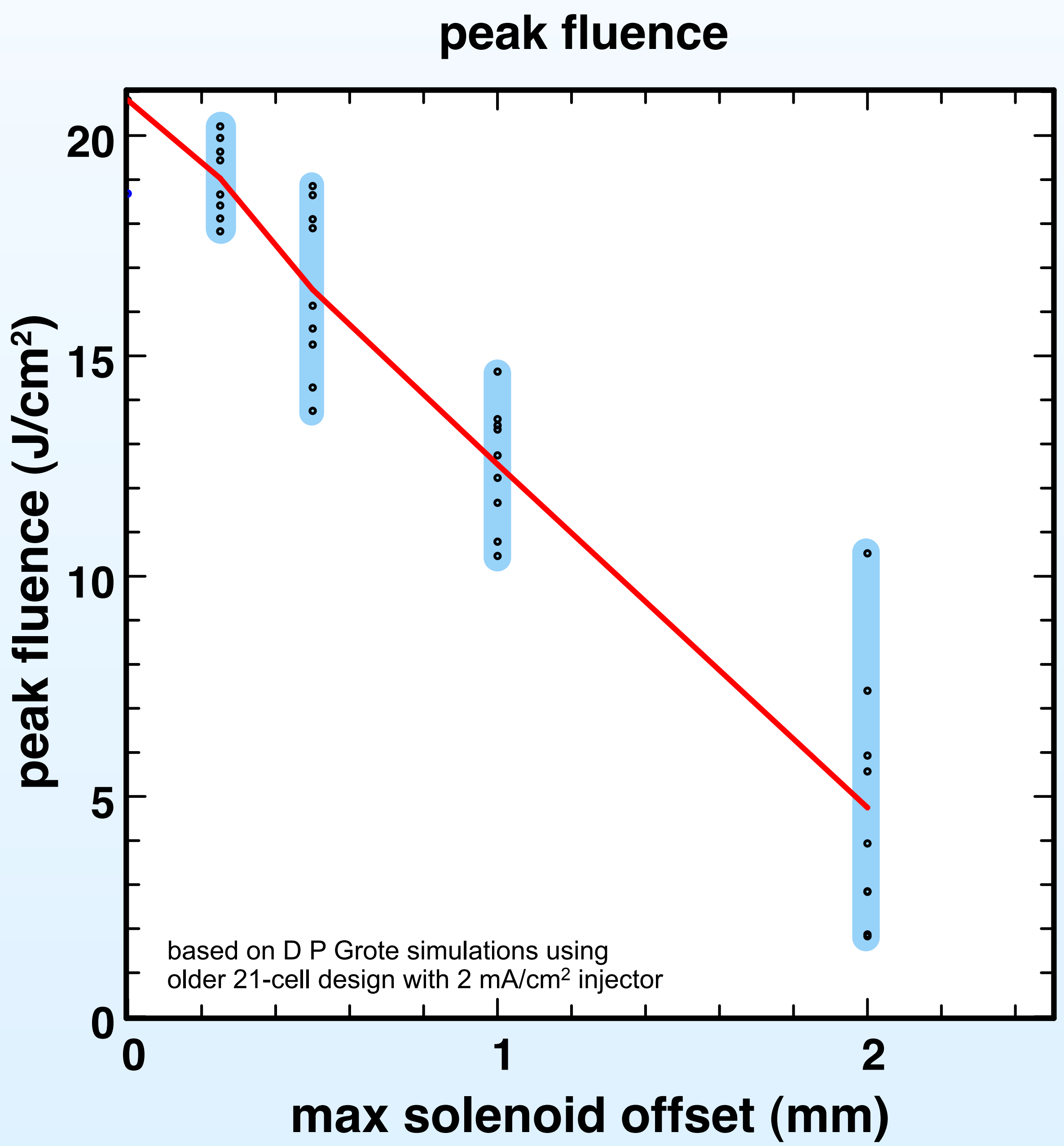
- method used in variant on “tuning V” used on DAHRT and ETA II
  see Y-J Chen, *Nucl Instr and Meth A* 398, 139 (1997)
- function minimized penalizes corkscrew and offsets, and limits dipole strength

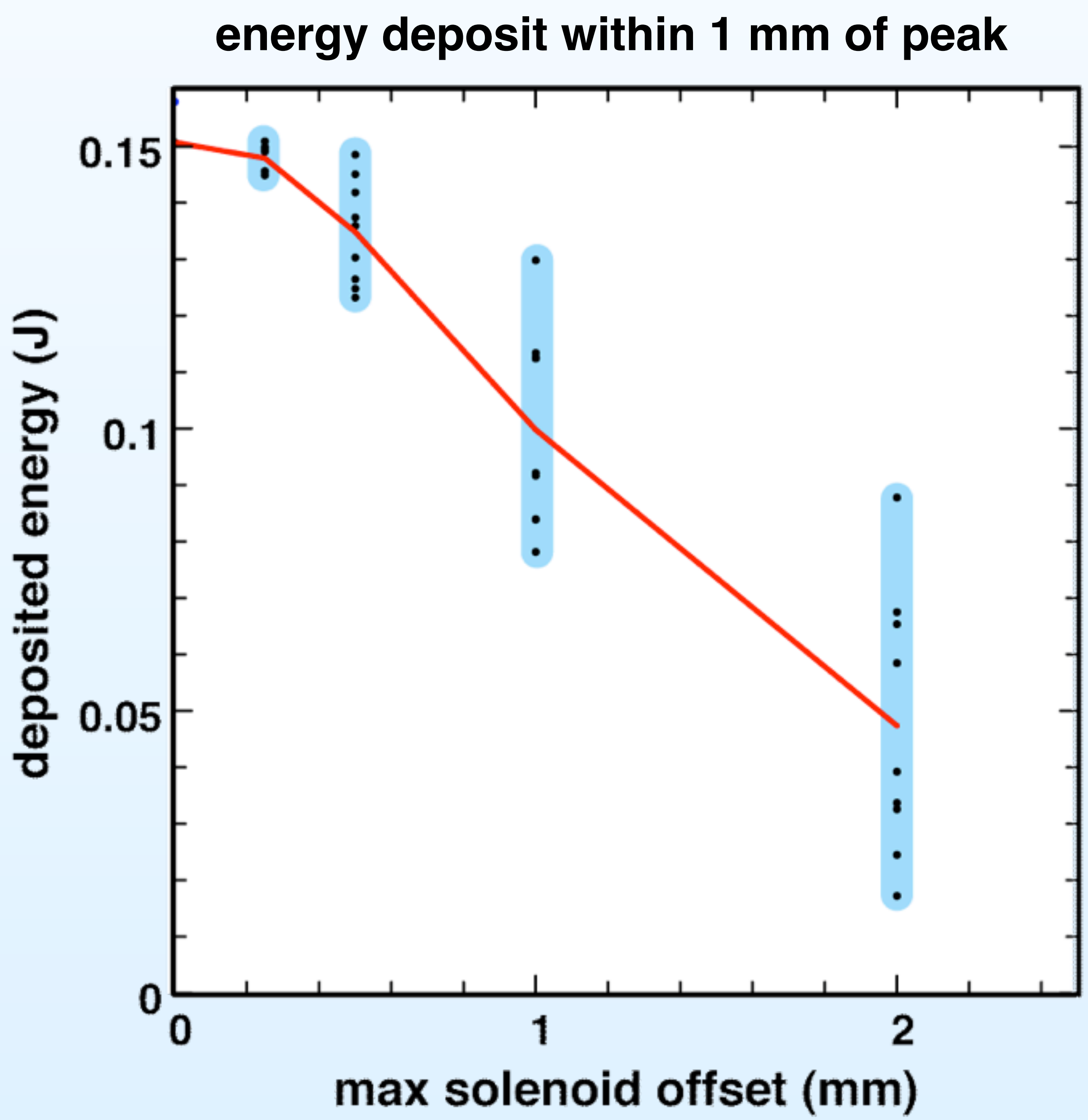


Final fluence shows some sensitivity to solenoid alignment errors

Warp 3-D shows only modest degradation for reasonable solenoid errors

- solenoid ends were displaced random x and y distances up to preset maximum offset
- energy deposition from the resulting offsets and tilts are shown for 8 trials
- changes in solenoid strength with temperature are still being studied

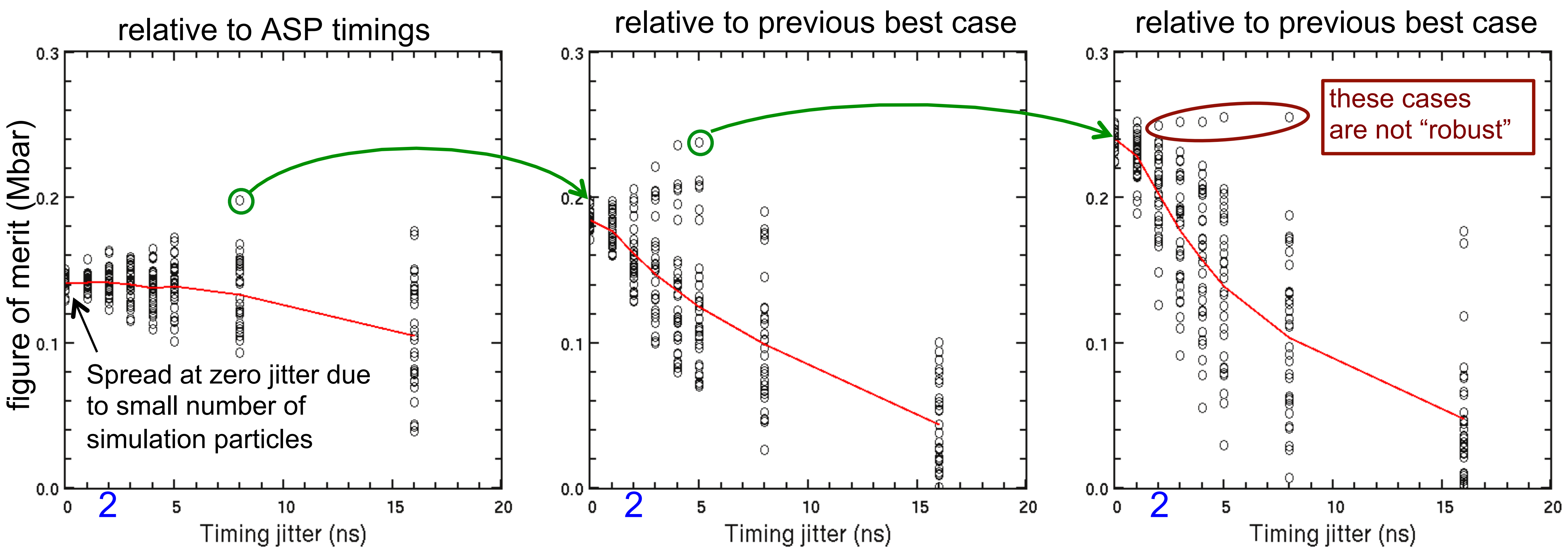




Warp runs clarify the effects of pulser timing jitter

figure of merit is an estimate of shock-wave pressure in Al foil target

- random shifts within a given maximum jitter were imposed on gap firing times
  - nominal NDCX-II spark gap jitter is 2 ns
- some jitter ensembles work better than ASP timings
  - the "best case" was used as the nominal timing in another round of jitter studies
  - successive "best cases" give better performance but greater average sensitivity to jitter



based on D P Grote simulations using older 15-cell design with 2 mA/cm^2 injector

ASP allows an efficient exploration of the NDCX-II design space

ASP designs that can be used in Warp without modification

- *r-z* Warp simulations with the identical lattice and waveforms give similar results provided
  - transverse focusing maintains a beam radius near that assumed in the HINJ model
  - ASP is initialized with density and velocity profiles that match injected Warp beam
- radial variation of gap fringe fields and space charge introduce minor discrepancies

the strategy of compression followed by acceleration seems workable

- maximizes use of ATA hardware
- achieves adequate energy with 20 acceleration cells and one energy-correction cell
- gives negligible increase in transverse emittance
- requires B_z fields of 2 T or less for transverse confinement
- final velocity tilt and average energy are insensitive to lattice details
- minimal particle loss to walls and to halo
- effects of solenoid misalignments appear manageable
  - with expected misalignments and no steering, beam reaches target with negligible loss
  - optimized dipole steering largely eliminates corkscrew and reduces final displacement
  - reduction in energy fluence on target due to solenoid misalignment appears modest
- nominal ASP design shows little sensitivity to random jitter in gap firing times

with little optimization, beam achieves needed final energy, spot size, and duration

NDCX-II experiments can also address HIF questions

non-neutral drift compression

- first half of accelerator imposes controlled velocity tilt
- space charge removes most of the tilt as beam duration reaches 70 ns
- 50:1 compression ratio is similar to driver requirements

beam head control

- NDCX-II beam resembles driver beam with most of flat-top removed
- ATA cores could separately control head or tail of uncompressed beam
- modified pulse-forming circuits would have to be added to compensation boxes

chromatic aberration in final focus

- final-focus solenoid could be place after any acceleration block
- beam tilt ranges from -5% to +10%
- diagnosing the beam at best radial focus would show effects of velocity variation

quadrupole transport with and without tilt

- a quadrupole section could be added after any acceleration block