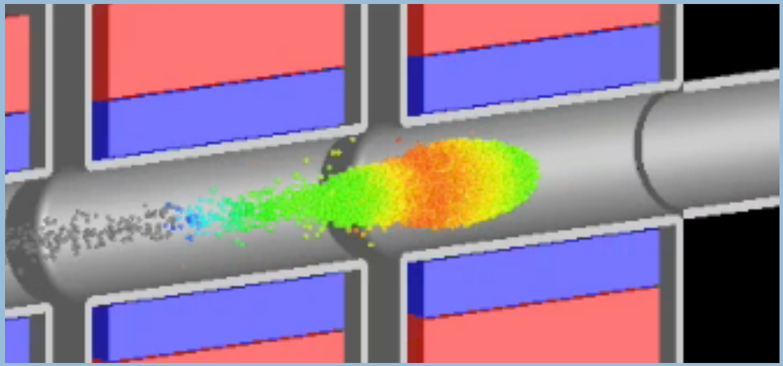
NDCX-II Physics Design Overview*



Beam traversing an acceleration gap

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Visit of the NAS Committee on Prospects for Inertial Confinement Fusion Energy Systems

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The Heavy Ion Fusion Science Virtual National Laboratory

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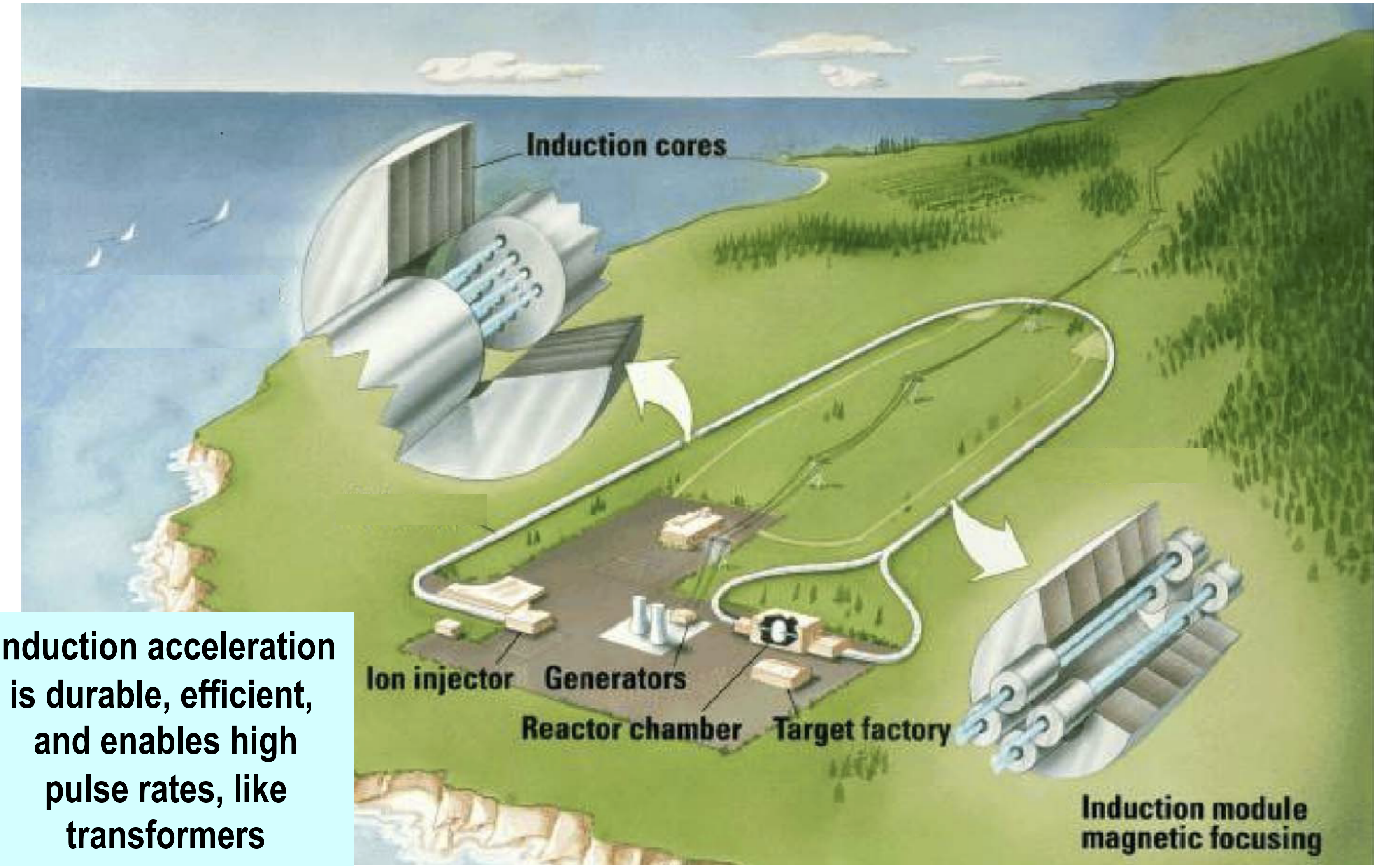
Heavy ion fusion driver based on induction acceleration with superconducting magnets enables 100's of TW peak power.



Induction acceleration is durable, efficient, and enables high pulse rates, like transformers

Heavy ion accelerators of multi-MJ fusion scale would be comparable in scale to today's large NP accelerators like GSI-FAIR, RHIC →economical for 1-2 GW_e baseload power plants.

Advantages of heavy ion fusion have long been recognized

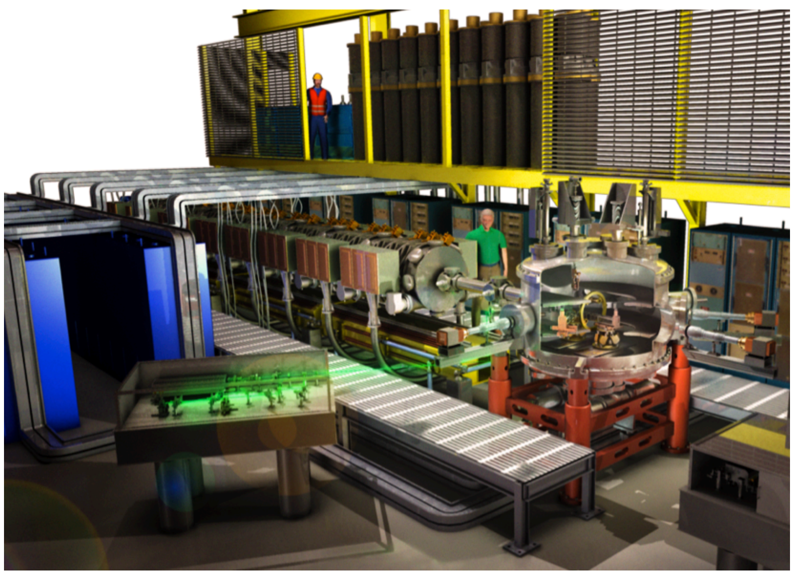
- **Accelerator knowledge base:** High-energy particle accelerators of MJ-scale beam energy have separately exhibited intrinsic efficiencies, pulse-rates, average power levels, and durability required for IFE.
- **Liquid-walled chambers:** Heavy ion beams can propagate through the vapor pressure of thick-liquid-protected chambers with 30 yr lifetimes.
- **Robust final optics:** Focusing magnets for ion beams avoid direct line-of-sight damage from target debris, neutron and gamma radiation.
- **Target injection:** Heavy ions can penetrate metal cases surrounding cryogenic-DT fuel, protects HIF targets in hot IFE chambers.
- **Competitive economics:** projected in several power plant studies, with class-C waste criteria satisfied.

Outline

- Brief NDCX-II overview
- Experiments relevant to HIF driver
- Experiments relevant to HIF focusing
- Experiments relevant to HIF targets
- Upgrade potential

The NDCX-II project is well underway

- DOE's Fusion Energy Sciences office approved NDCX-II in 2009.
- $11 M of funding was provided via the American Recovery and Reinvestment Act.

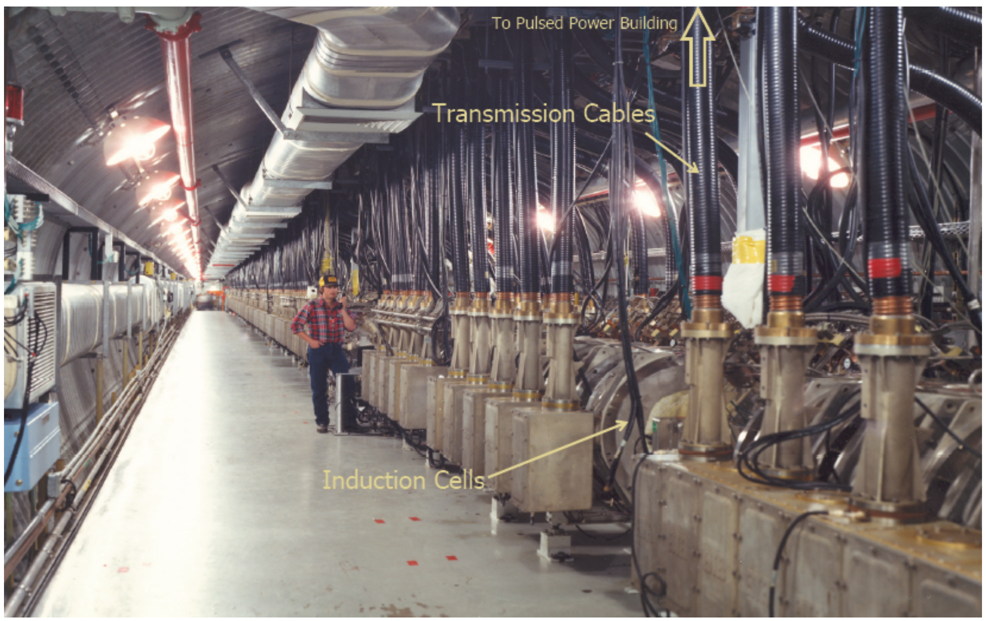


- Construction of the initial configuration began in July, 2009,
- Project completion is due by March, 2012; we are aiming for the fall of 2011.
- Commissioning will then begin, followed by target experiments.

LLNL gave us 50 induction cells from the ATA electron accelerator

- Ferrite cores offer 1.4 x 10^{-3} Volt-seconds
- Blumlein voltage sources offer 200-250 kV with FWHM duration of 70 ns
- Longer beam at front end needs custom voltage sources < 100 kV
- Ion beam requires stronger (3T) pulsed solenoids and other cell modifications

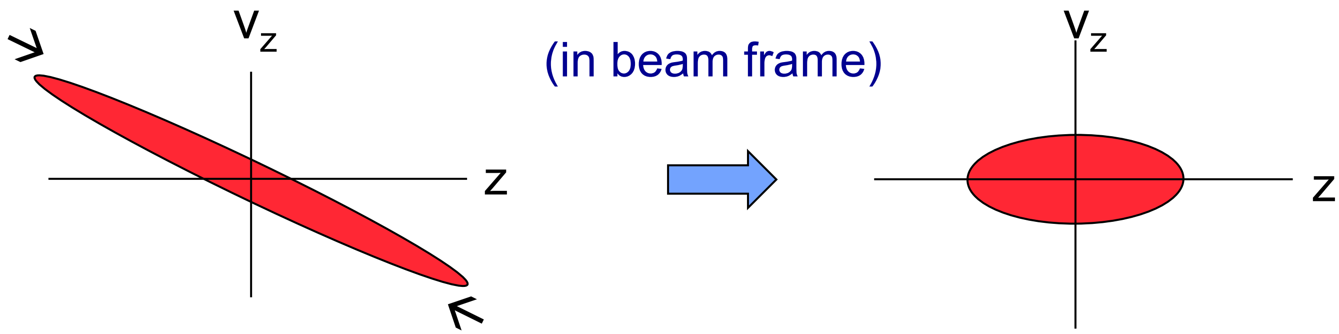
Advanced Test Accelerator (ATA)



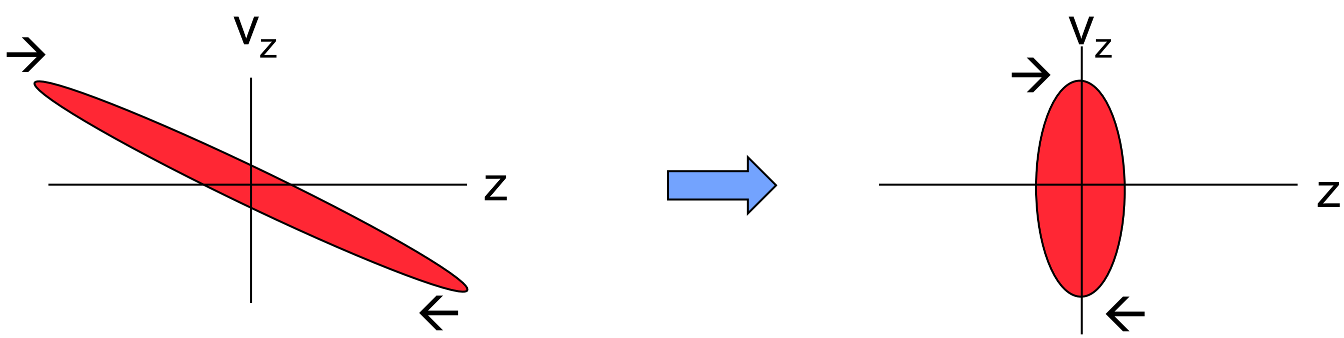
The drift compression process is used to shorten an ion bunch

- 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:



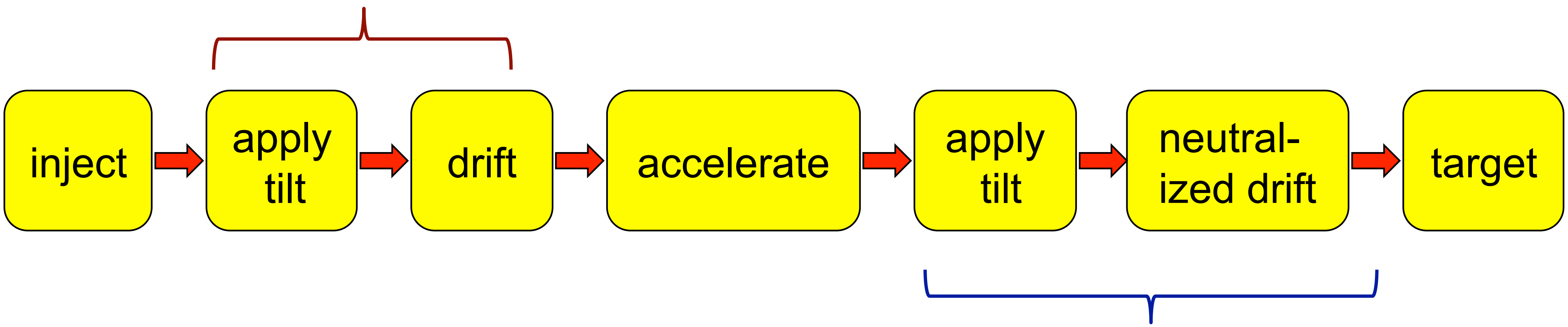
- In neutralized drift compression, the space charge force is eliminated, resulting in a shorter pulse but a larger velocity spread:



The drift compression concept 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

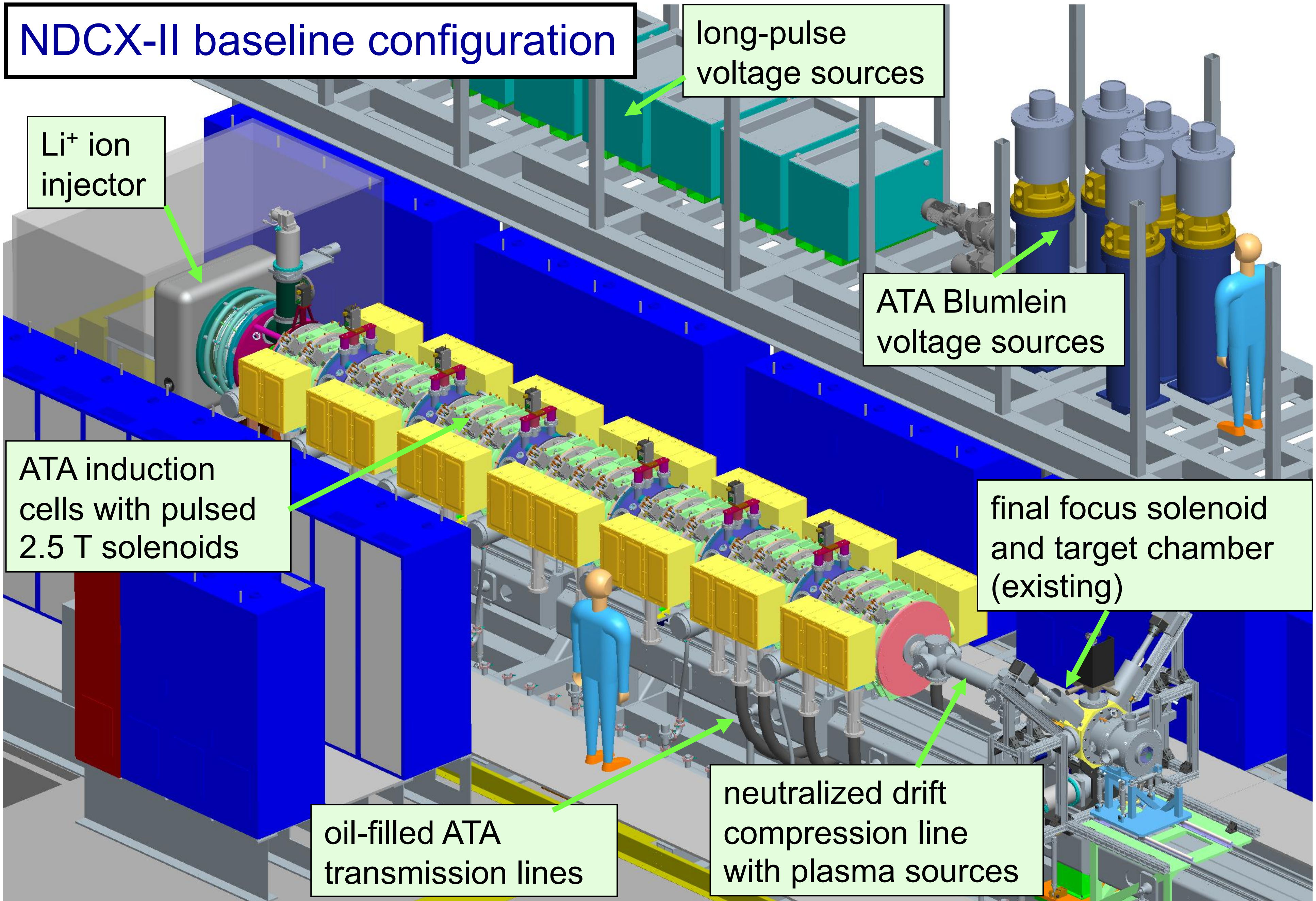


Final neutralized drift compression onto the target

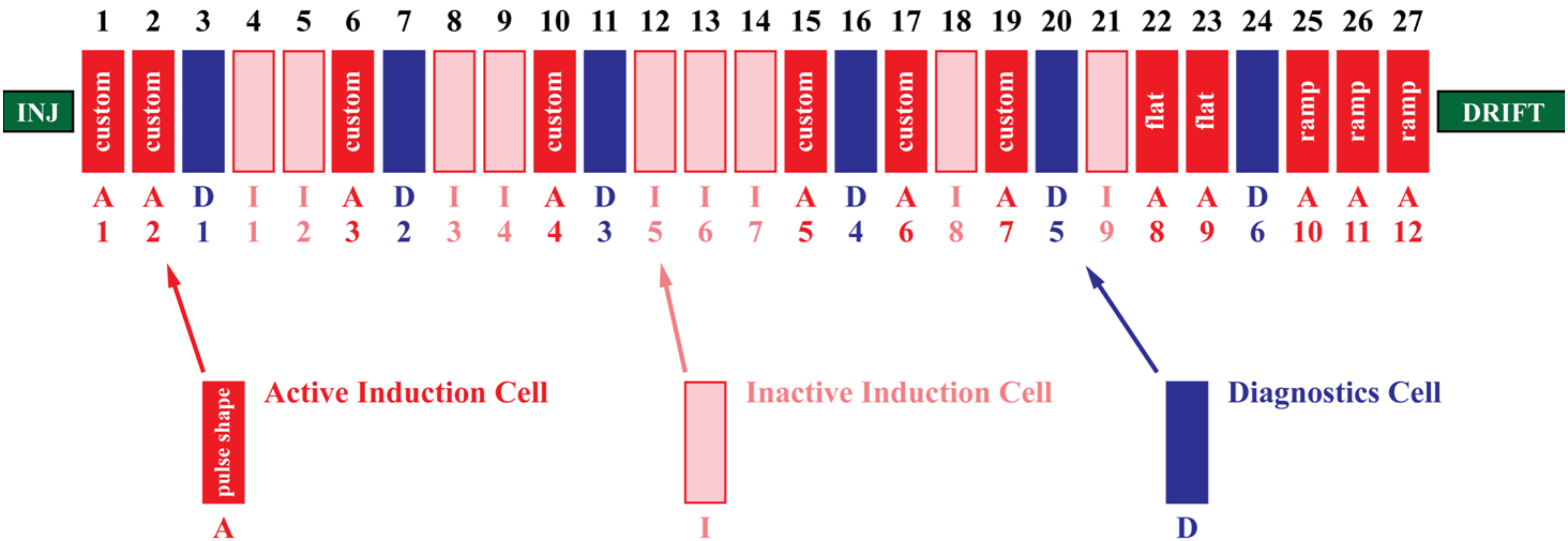
- Electrons in plasma move so as to cancel the beam's electric field
- Require $n_{plasma} > n_{beam}$ for this to work well

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

NDCX-II baseline configuration



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



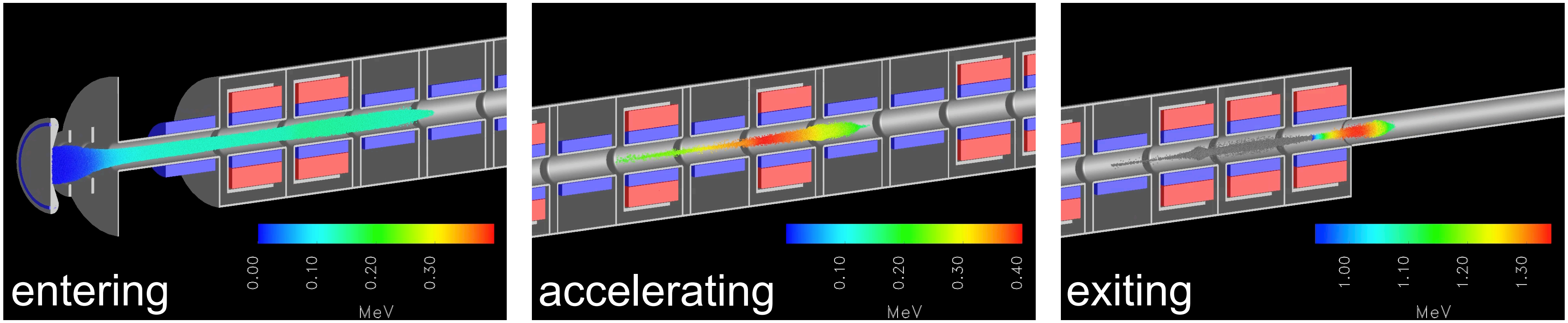
- 27 lattice periods after the injector
- 12 active induction cells
- Beam charge ~50 nano-Coulombs
- FWHM < 1 ns
- Kinetic energy ~ 1.2 MeV

NDCX-II will be far more capable than NDCX-I

	NDCX-I (typical bunched beam)	NDCX-II 12-cell (r,z simulation)
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 are from (r,z) Warp runs (no misalignments), and assume 1 mA/cm^2 emission, no timing or voltage jitter in acceleration pulses, no jitter in solenoid excitation, perfect neutralization, and a uniform non-depleted source; they also assume no fine energy correction (e.g., tuning the final tilt waveforms)

Simulations enabled development of the NDCX-II physics design



- New, fast 1-D (longitudinal) particle-in-cell code ASP enabled finding an attractive operating point within the large parameter space
- Injector, transverse beam confinement, and final focusing were developed using the Warp code in (r,z) geometry
- We used 3-D Warp calculations to assess performance in the presence of imperfections, set tolerances

These same tools will enable detailed comparisons of beam measurements and simulations, using "synthetic diagnostics"

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

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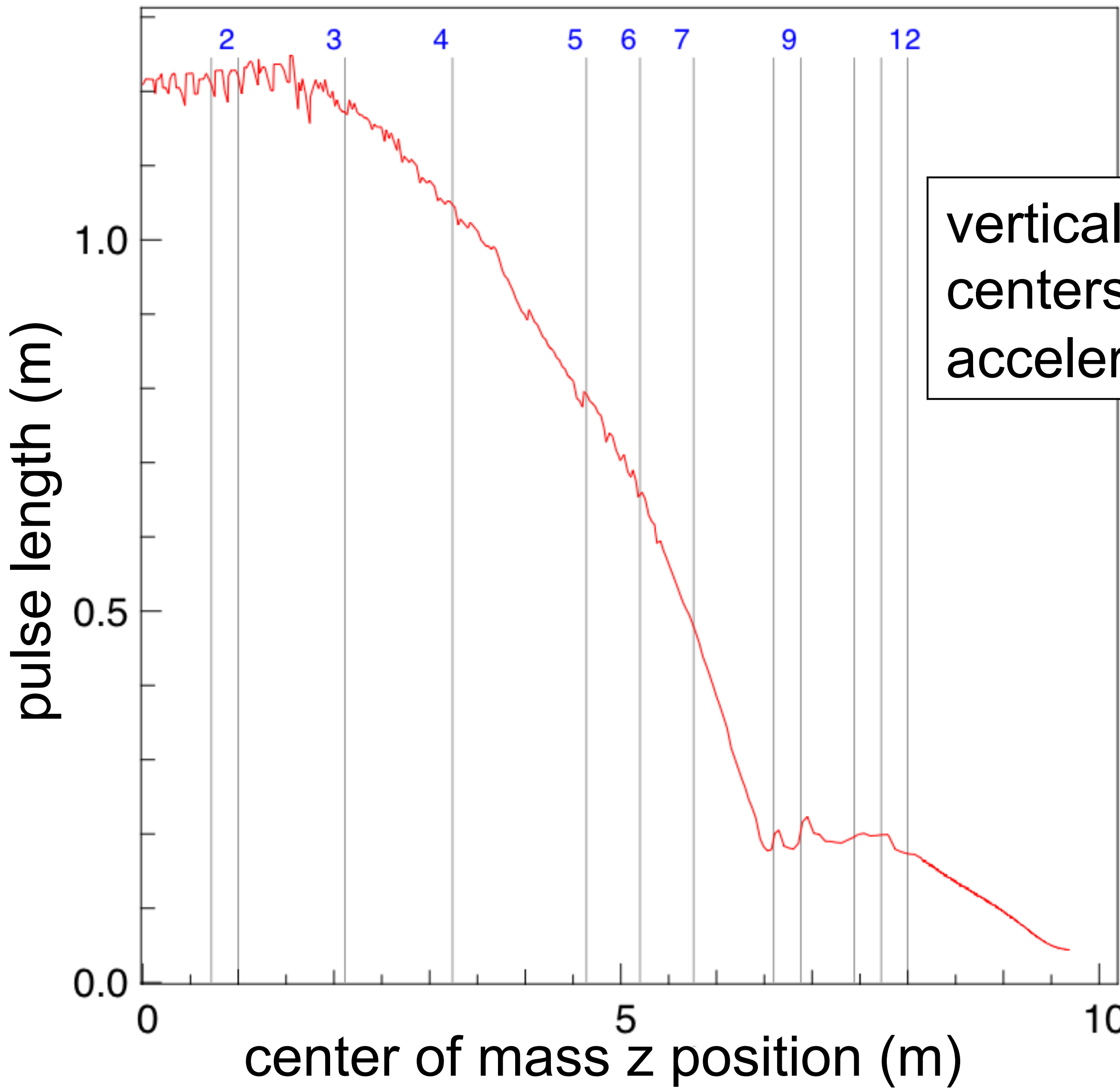
Pulse length vs. z, as developed using 1-D ASP simulation



vertical lines denote centers of active acceleration gaps

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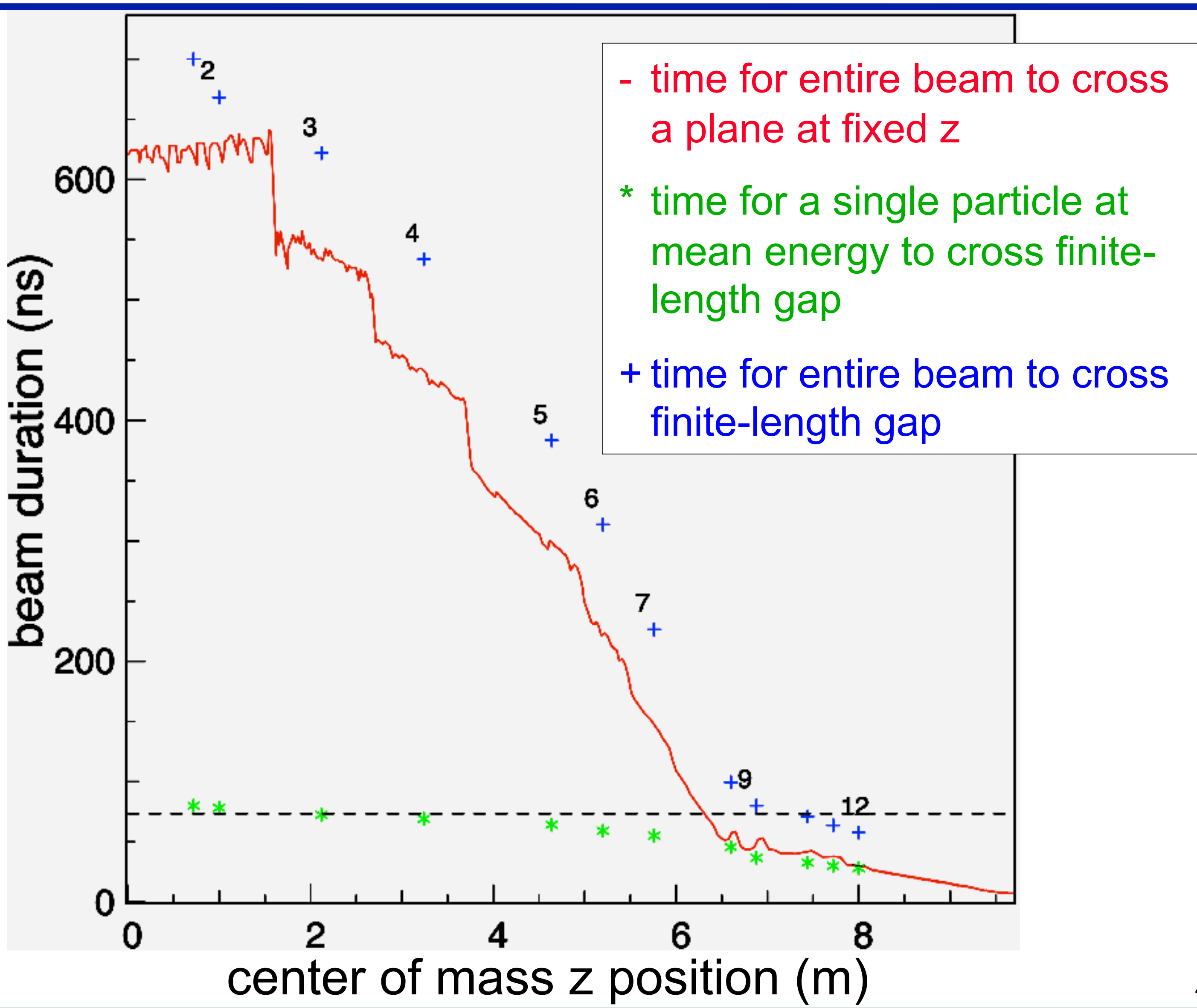
Pulse duration vs. z: the entire beam transit time is key



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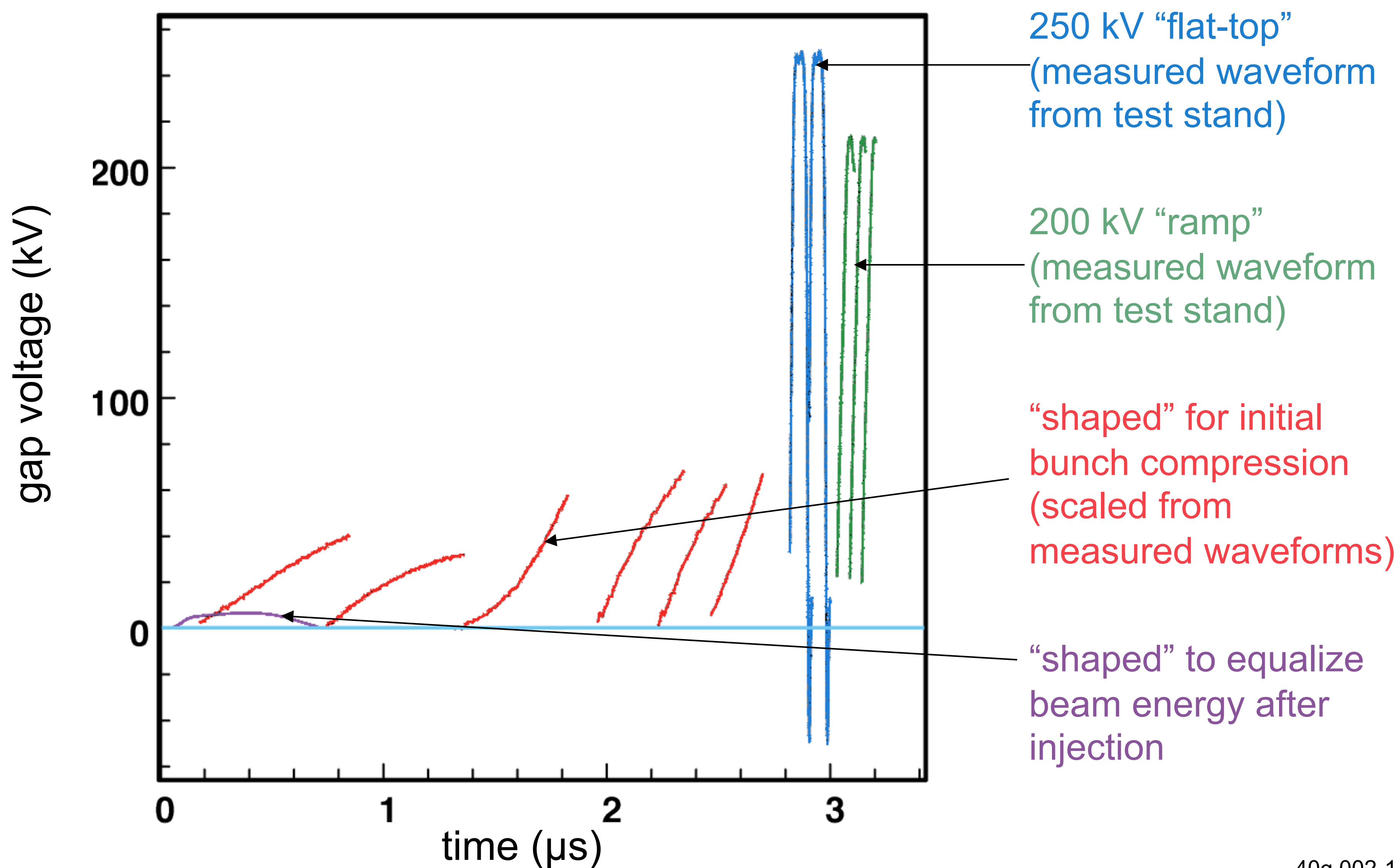
Voltage waveforms for all gaps



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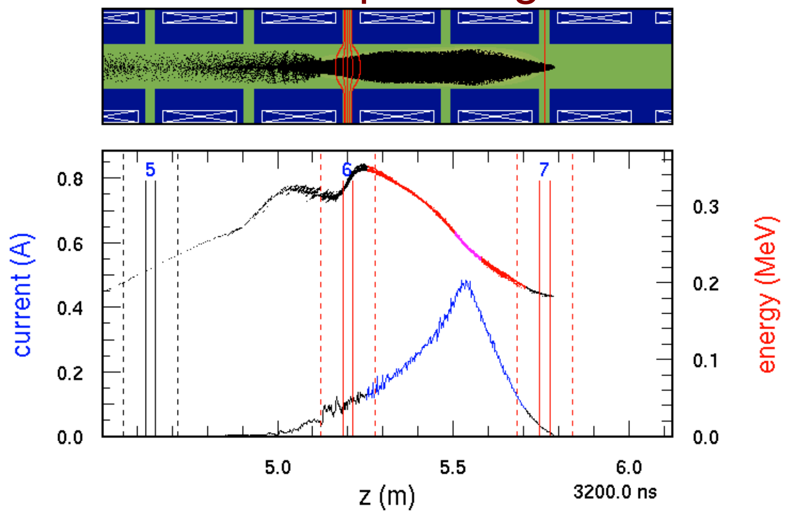
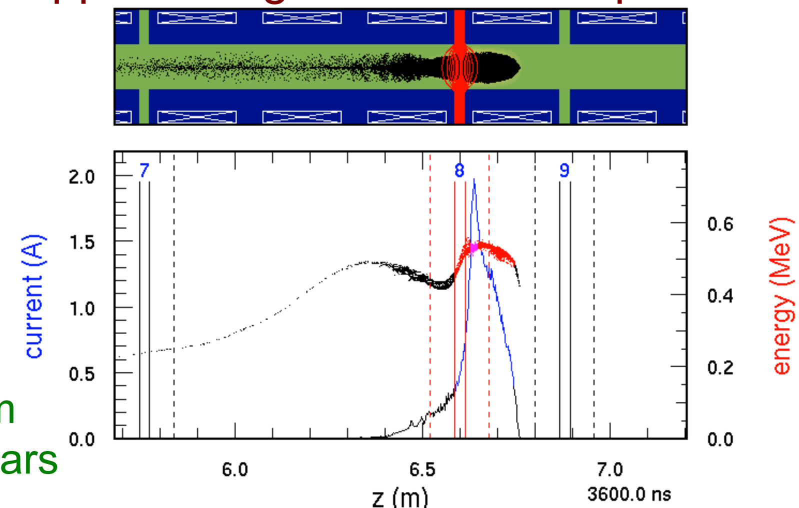
Snapshots from a Warp (r,z) simulation

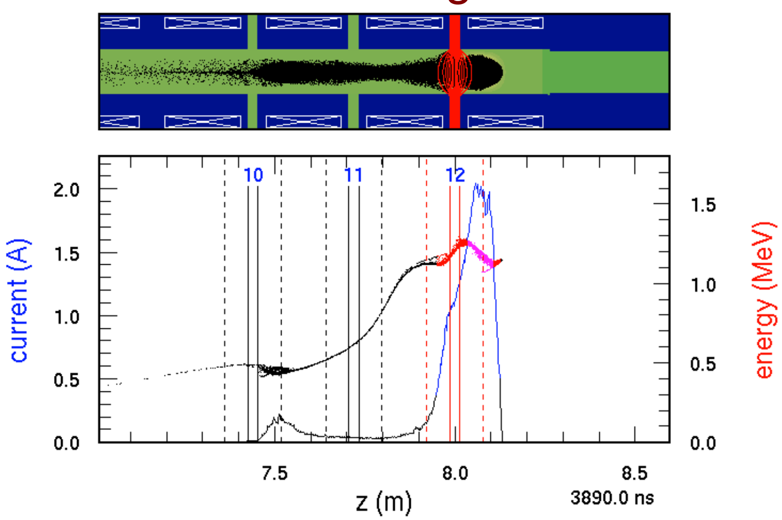
compressing



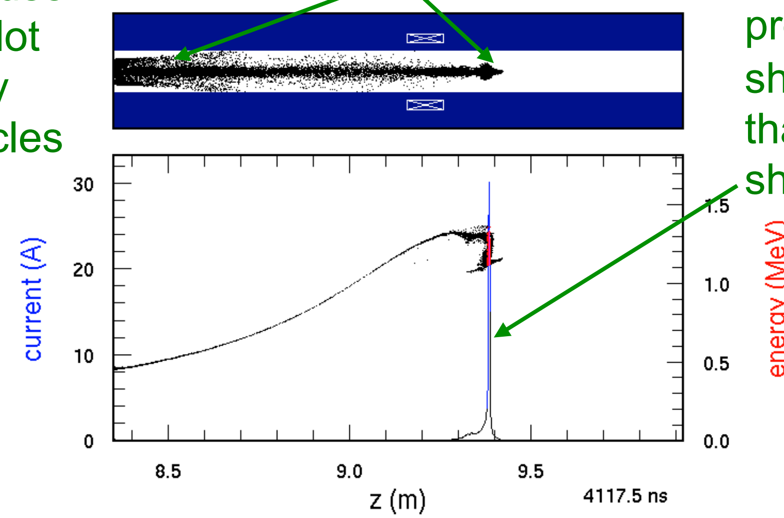
approaching maximum compression



exiting



at focus



Beam appears long because we plot many particles …

… but current profile shows that it is short

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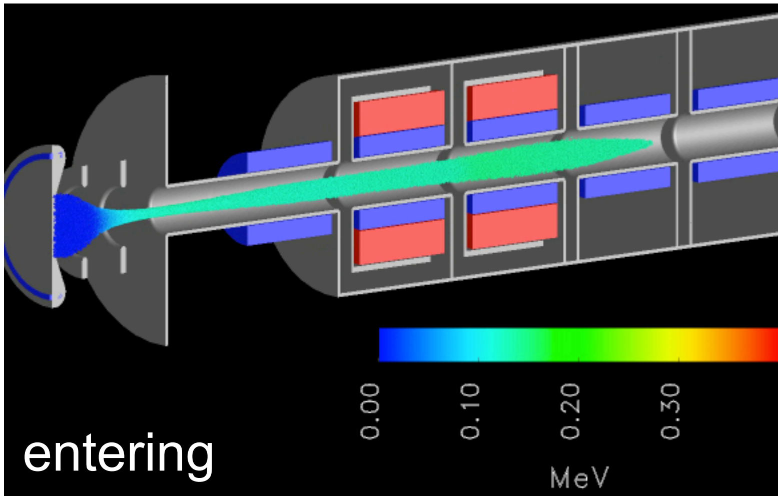
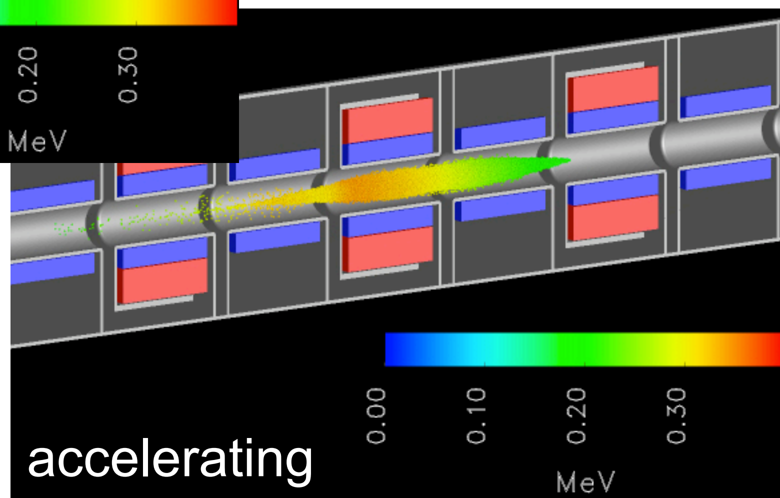
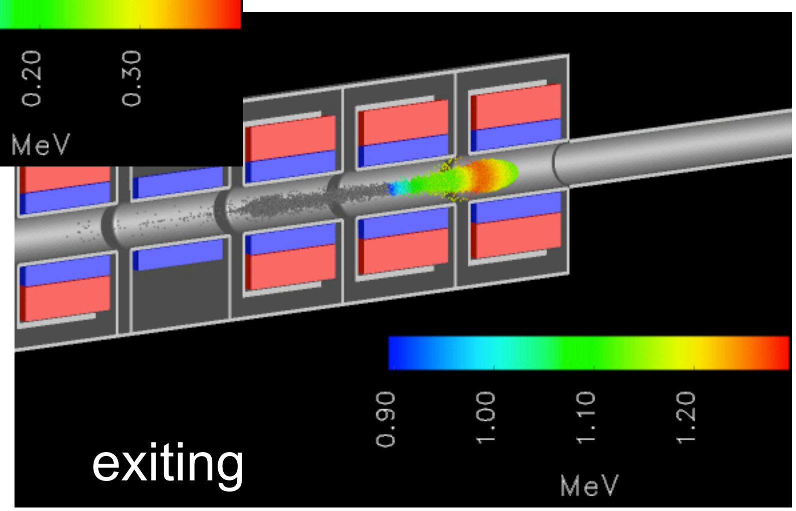
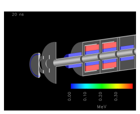
Video: Warp simulation of 12-cell NDCX-II configuration









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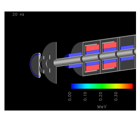

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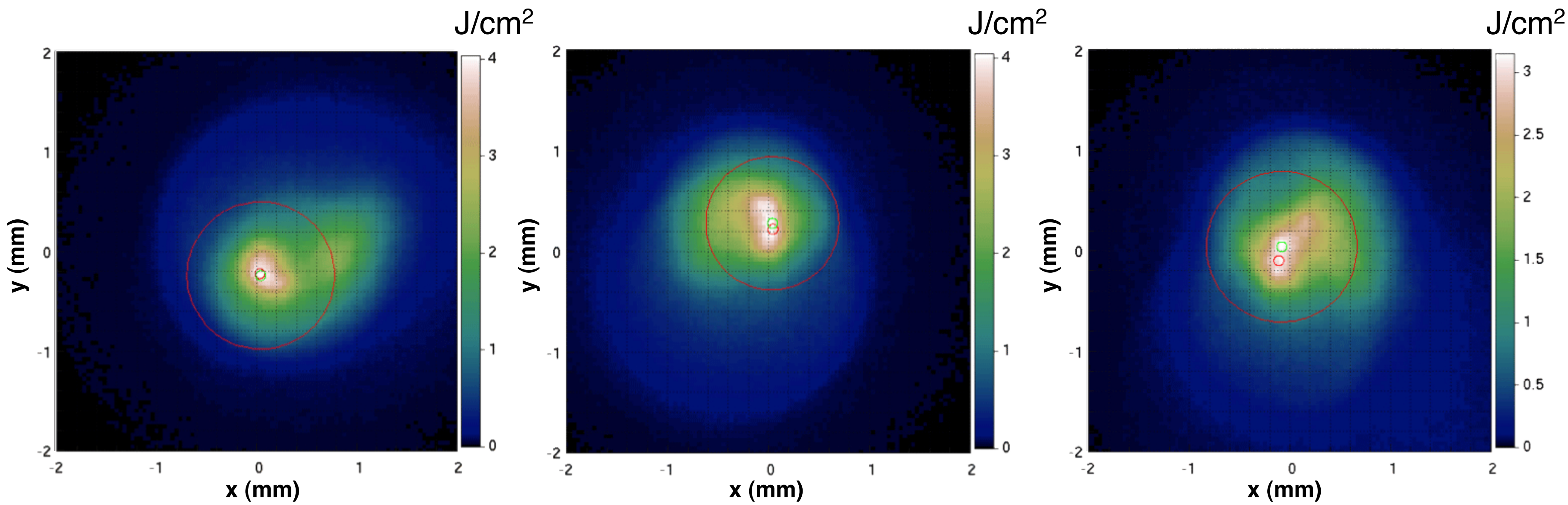
Warp runs illustrate effects of solenoid alignment errors

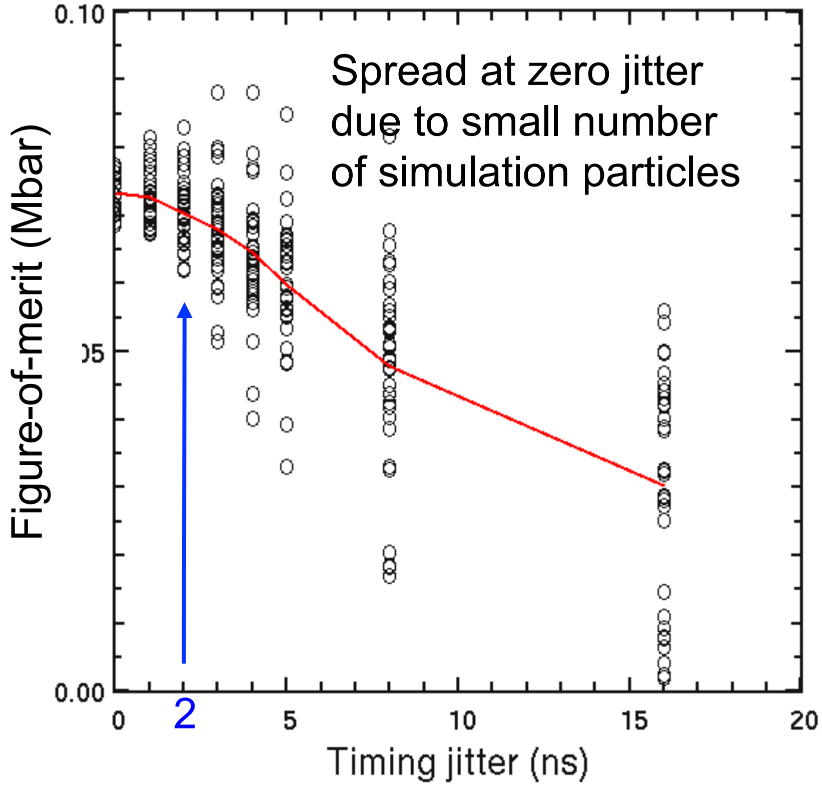
Plots show beam deposition for three ensembles of solenoid offsets

- maximum offset for each case is 0.5 mm
- red circles include half of deposited energy
- smaller circles indicate hot spots



Ensembles of Warp runs indicate only minor degradation due to:

pulser timing jitter



- Random timing shifts were imposed on the accelerating voltage pulses.
- Nominal NDCX-II spark-gap jitter is 2 ns

This capability will be useful for studies of HIF drivers.

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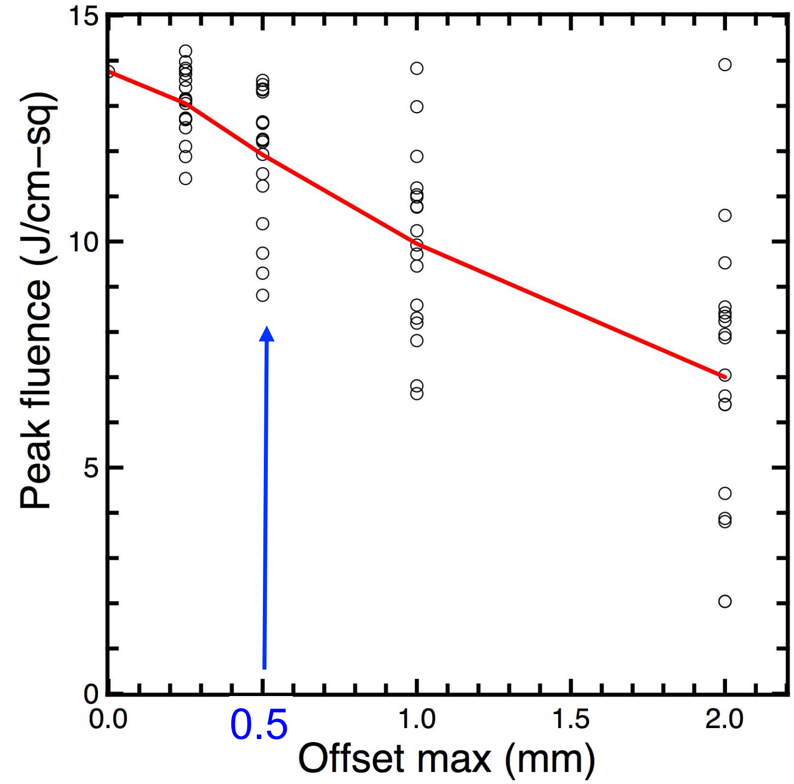
magnet misalignment



- Random offsets were imparted to the solenoid ends.
- Nominal NDCX-II tolerance is 0.5 mm
- Beam "steering" via dipole magnets will center beam and minimize "corkscrew" distortion.

35g-15 (older 15-cell design)

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)

Outline

- Brief NDCX-II overview
- Experiments relevant to HIF driver
- Experiments relevant to HIF focusing
- Experiments relevant to HIF targets
- Upgrade potential

The NDCX-II accelerator *embodies* beam physics relevant to an HIF driver

- Collective beam dynamics:
  - Space-charge force is very large (“generalized perveance” up to 0.01)
  - Driver-like compression of non-neutral beam (in the NDCX-II accelerator)

    Space charge removes “tilt” as pulse compresses from ~500 to ~70 ns
  - Longitudinal beam confinement and control

- Non-ideal effects include:
  - Emittance growth (phase-space dilution) and “halo” formation
  - Beam - plasma interactions
  - Aberrations in final focus
  - Stray “electron cloud” (could steer beam into pipe wall)

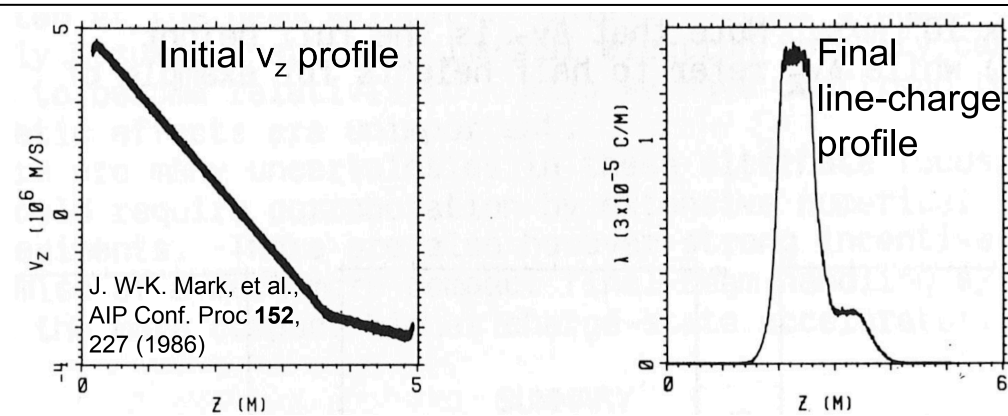
    All (or almost all) gaps run at ≥ 30 kV, while beam potential is ≤ 7 keV, so gap fields should sweep electrons from beam

These are among the first topics we’ll study

We propose using NDCX-II extensions to study …

- how well space charge can "stagnate" the compression to create a mono-energetic beam at final focus.

- how well the beam current can be controlled during drift compression for target pulse-shaping



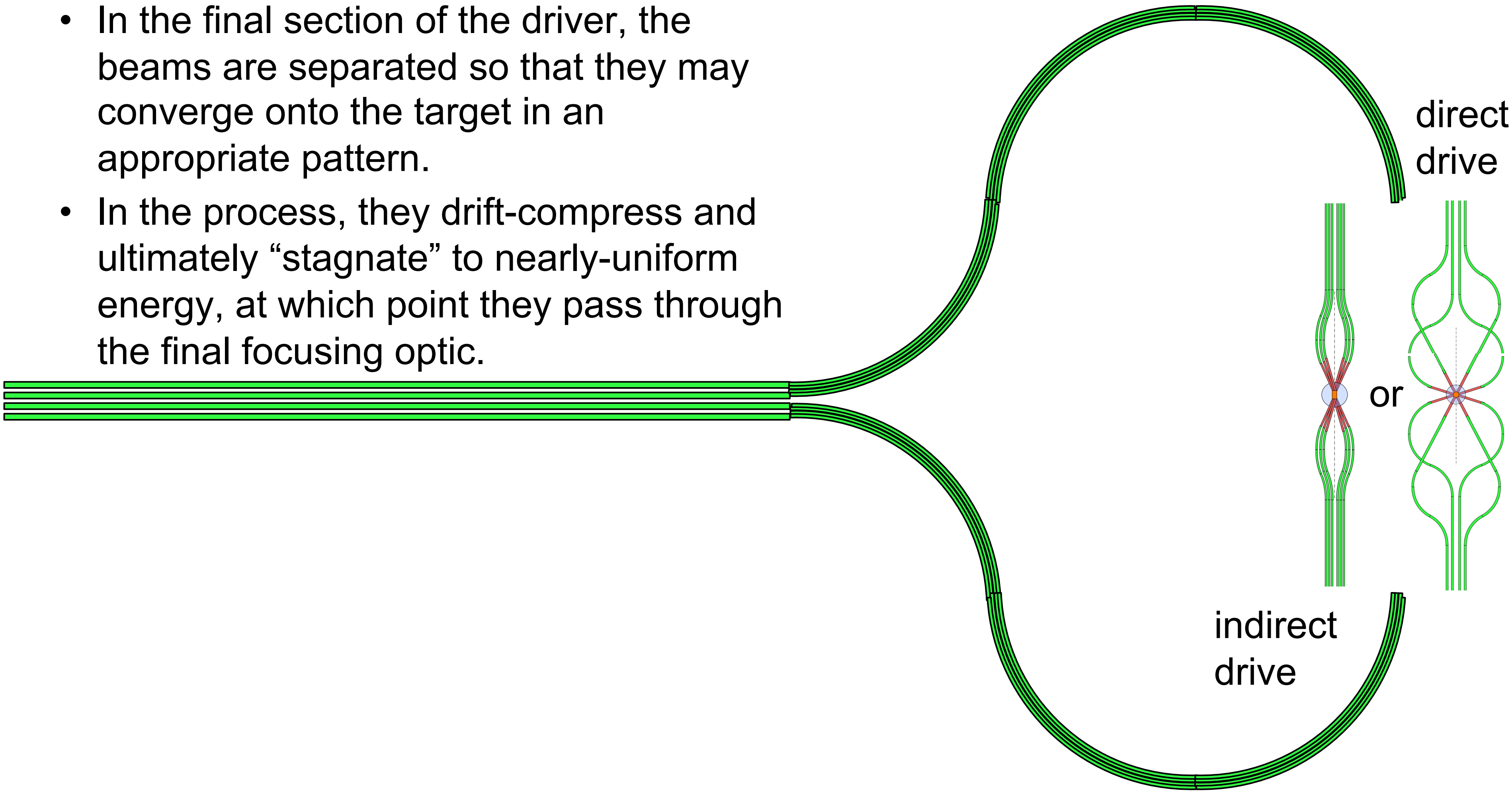
- how well can we compress a beam while bending it:
  - "achromatic" design, so that particles with all energies exit bend similarly
  - emittance growth due to dispersion in the bend

- aberrations in neutralized and vacuum @ final focus (solenoids vs quadrupoles)

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

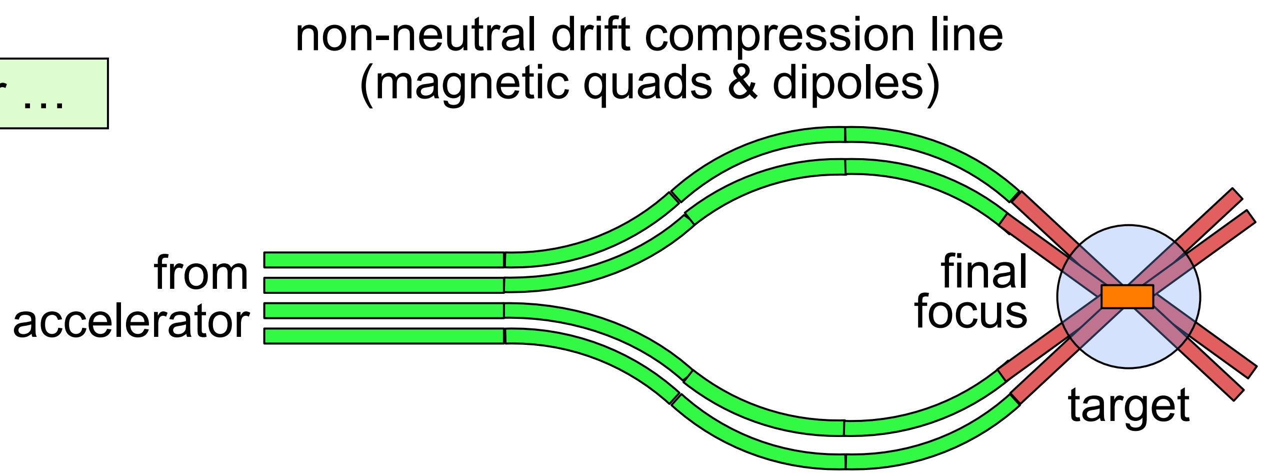
NDCX-II experiments can model the final sections of a driver

- In the final section of the driver, the beams are separated so that they may converge onto the target in an appropriate pattern.
- In the process, they drift-compress and ultimately "stagnate" to nearly-uniform energy, at which point they pass through the final focusing optic.

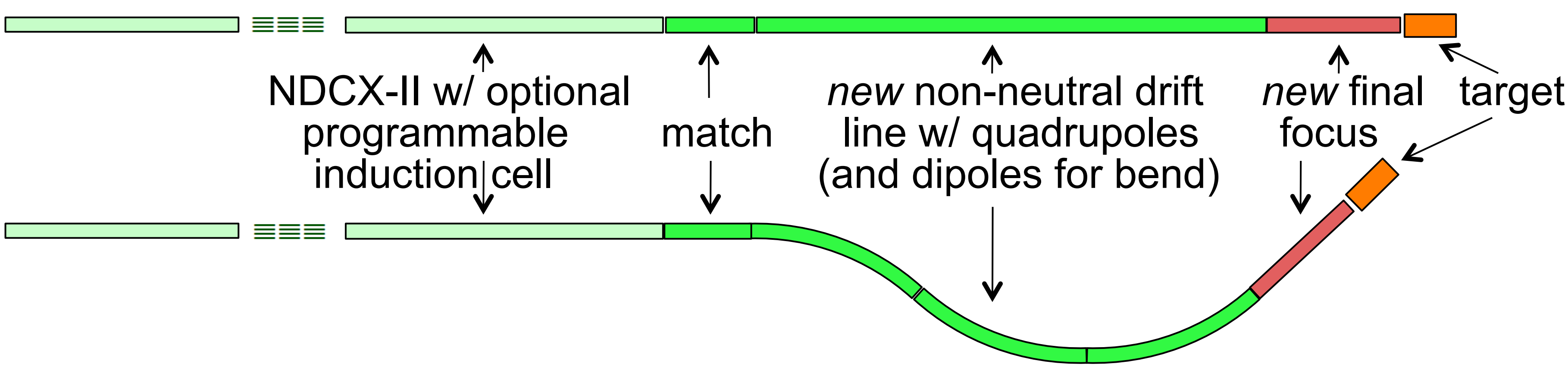


Experiments on NDCX-II can explore non-neutral compression, bending, and focusing of beams in driver-like geometry

In a driver …

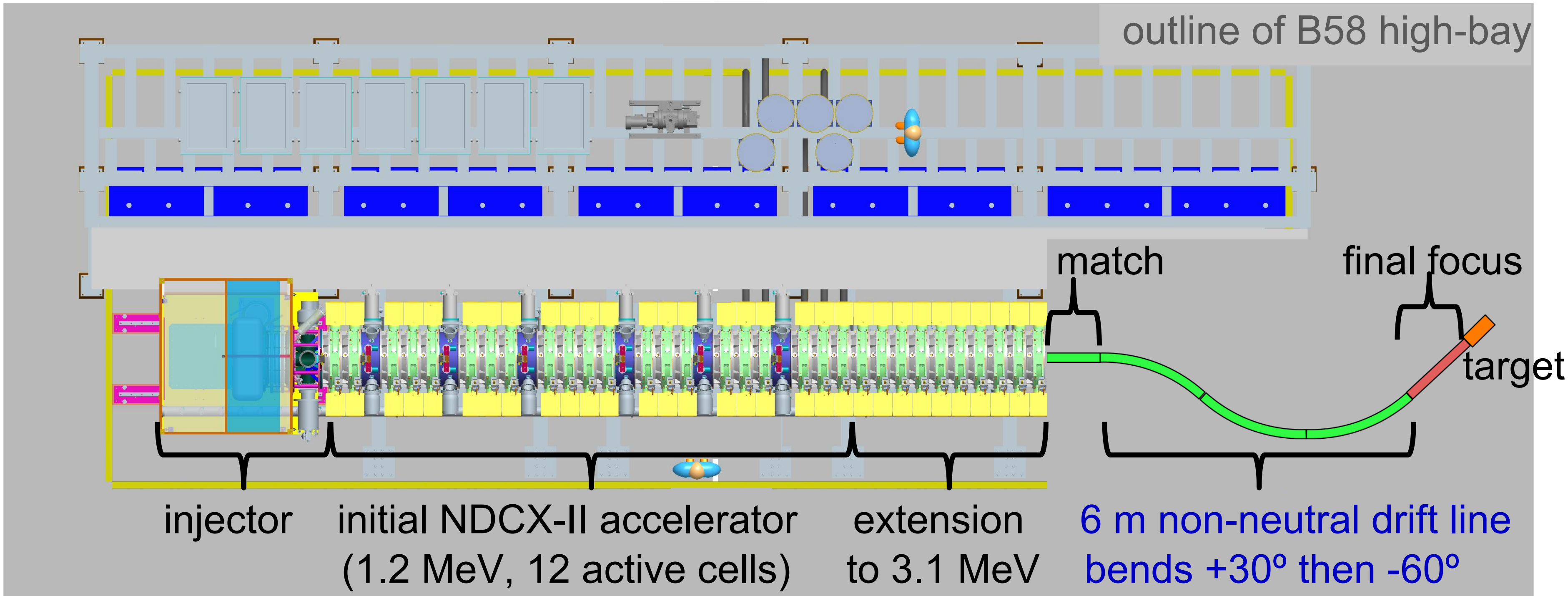


On NDCX-II, two configurations to test …



Non-neutral drift / bend / focus experiment in LBNL's Building 58

… will serve to validate our "achromat" concept (ions of all energies exit bend similarly) and quadrupole focusing onto a target, for space-charge-dominated beams



For a head-to-tail velocity tilt of +/- 5% :

- Pulse length of 0.6 m decreases to 0.083 m, with stagnation beyond the bend end at 6.5 m
- Current of 0.5 A increases to 3.6 A

Pipe radius = 3.0 cm

30 water-cooled DC magnetic quads w/ iron poles:

Quad spacing = 20 cm, L_{eff} = 13.33 cm

Bend field 0.173 T continuous (combined function)

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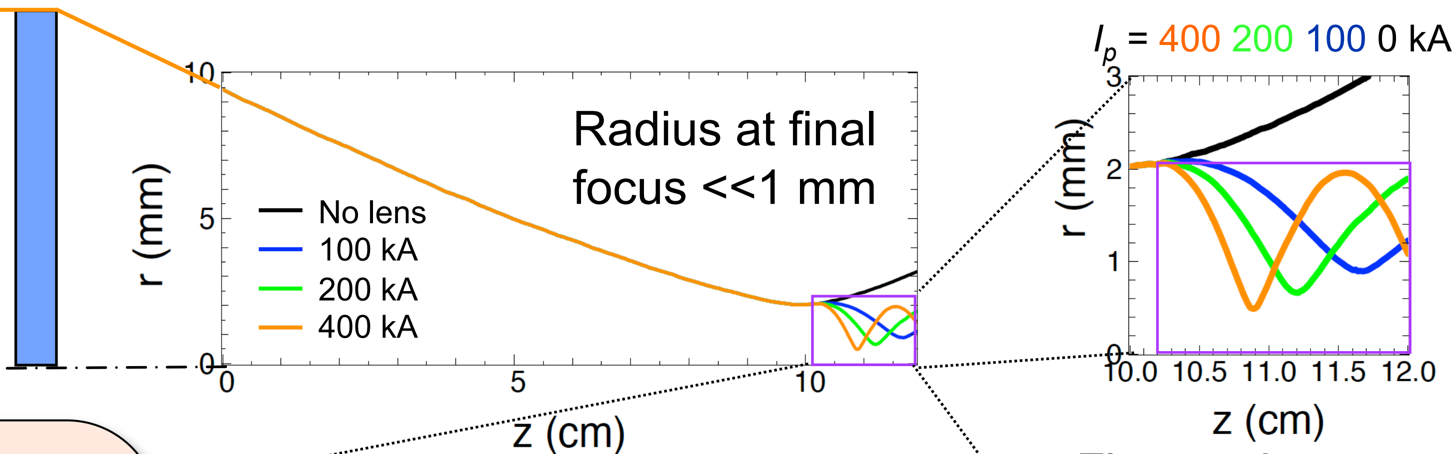
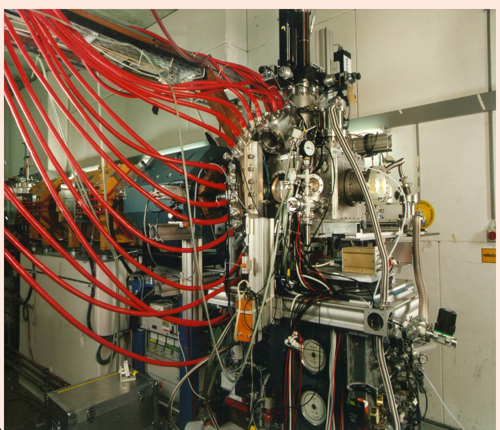
NDCX-II experiments can explore quadrupole focusing and two-stage focusing using a second-stage "B_θ" plasma lens

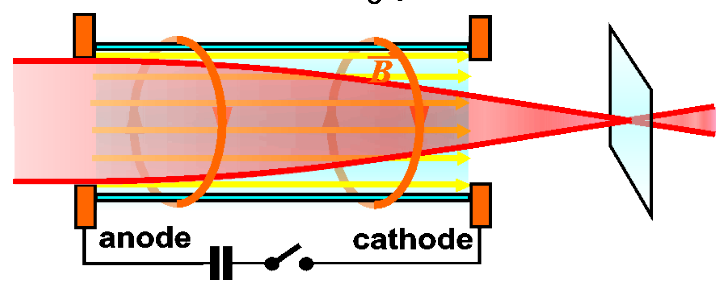
Conventional final focus: solenoid *then* quadrupoles



GSI plasma lens (I_p=240 kA)

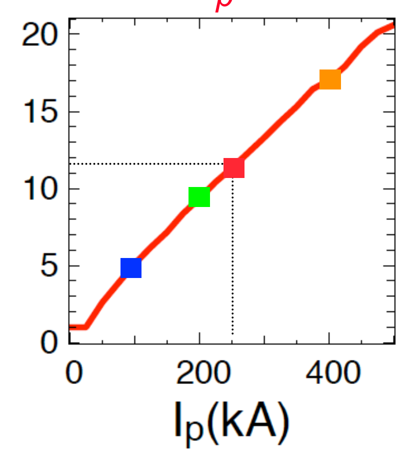


Windowless B_θ plasma lens



2 mm radius
0.5-1.5 cm length
I_p = 100-500 kA

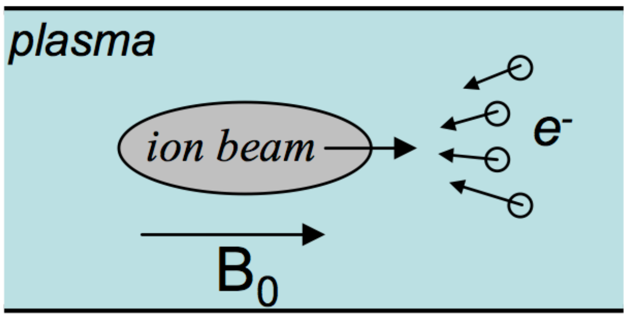
Fluence increase
>10x at I_p=250 kA



From Warp simulation
(ideal B_θ, neutralization)

Beam self-focusing force is greatly enhanced, relative to magnetic self-pinching, by a weak solenoid B field (~100 G)

Enhanced focusing is provided by a strong radial electric field from beam-induced polarization of the magnetized plasma background.

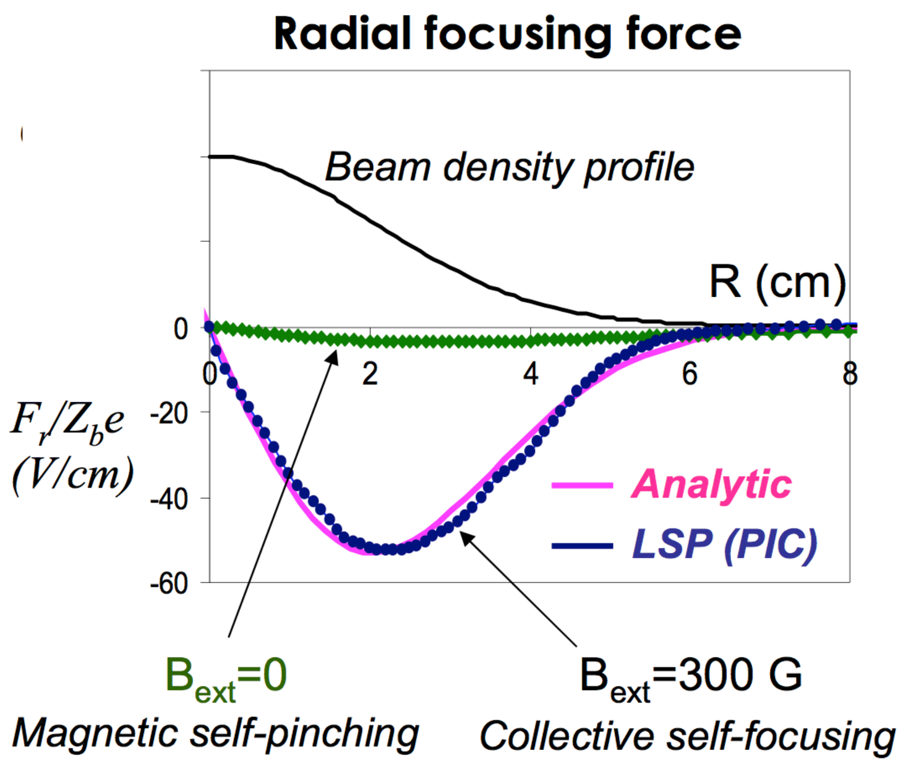


Provided the beam current is neutralized, *i.e.*, $Z_b n_b v_b = n_e v_{ez}$:

$$F_r = Z_b^2 m_e v_b^2 \frac{1}{n_e}\frac{dn_b}{dr}$$

Relative focusing strengths:
NDCX-I: $F_r L_{drift} / F_{sol} L_{sol}$ ~ 0.04
NDCX-II: $F_r L_{drift} / F_{sol} L_{sol}$ ~ 0.5

M. Dorf, et al., PRL 103, 075003 (2009)



requires:

$r_{ge} << r_b << c/\omega_{pe}$ $\quad r_{ge} \equiv \frac{v_b}{\omega_{ce}}\left(1+\frac{\omega_{ce}^2}{\omega_{pe}^2}\right)^{1/2}$

⇒ $\omega_{ce} >> 2\beta_b\omega_{pe}$

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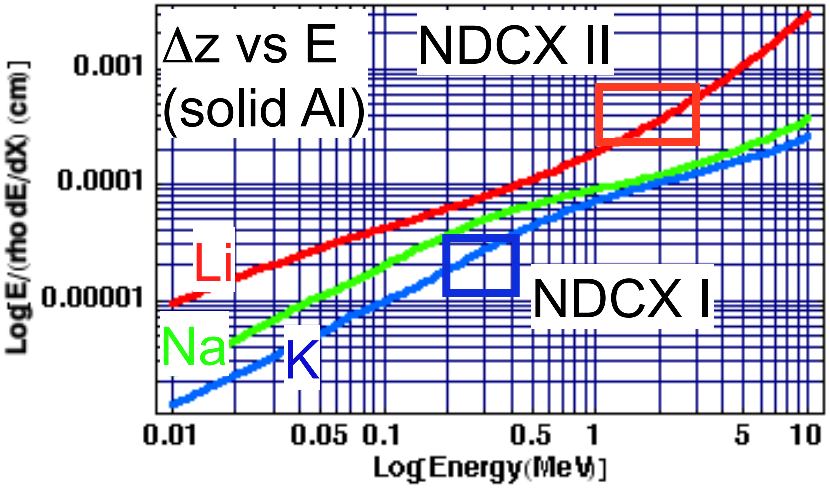
NDCX-II will enable study of ion beam energy coupling physics

Range increases with energy :



For NDCX-II we may use 10% Al foam:
Δz ≈ 20 μ (k.e. / 1 MeV)

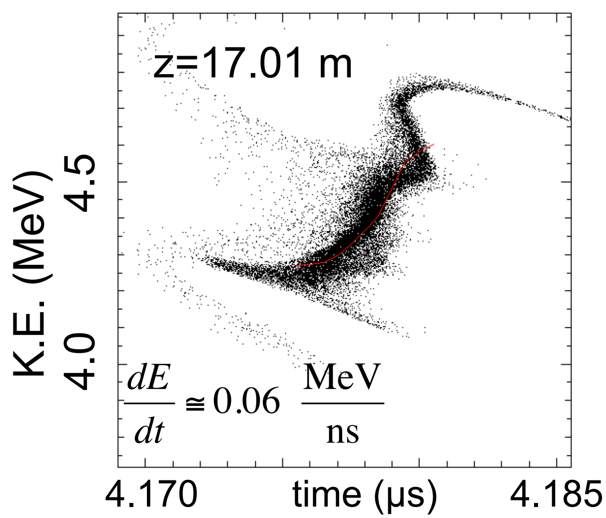
To "follow a shock", (where $v_{shock} \sim c_s$) the energy slew must be sufficiently rapid:

$$\frac{dE}{dt} \cong 0.10 \ \frac{\text{MeV}}{\text{ns}}$$

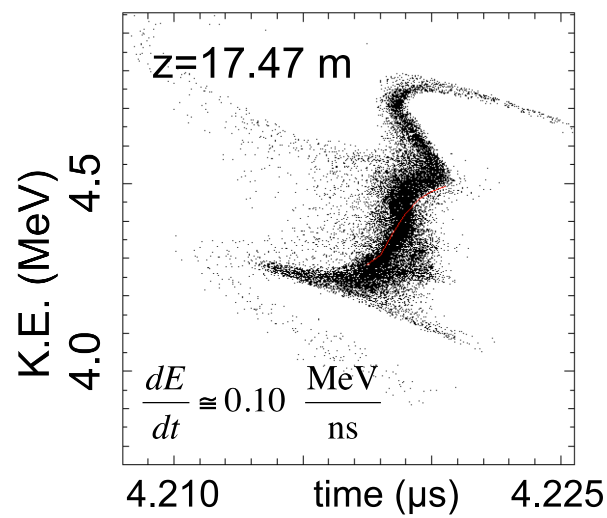
Placing foil upstream of best focus is a simple way to achieve energy ramp.

Using Warp, we looked at the energy slew rate, here on an extended NDCX-II.

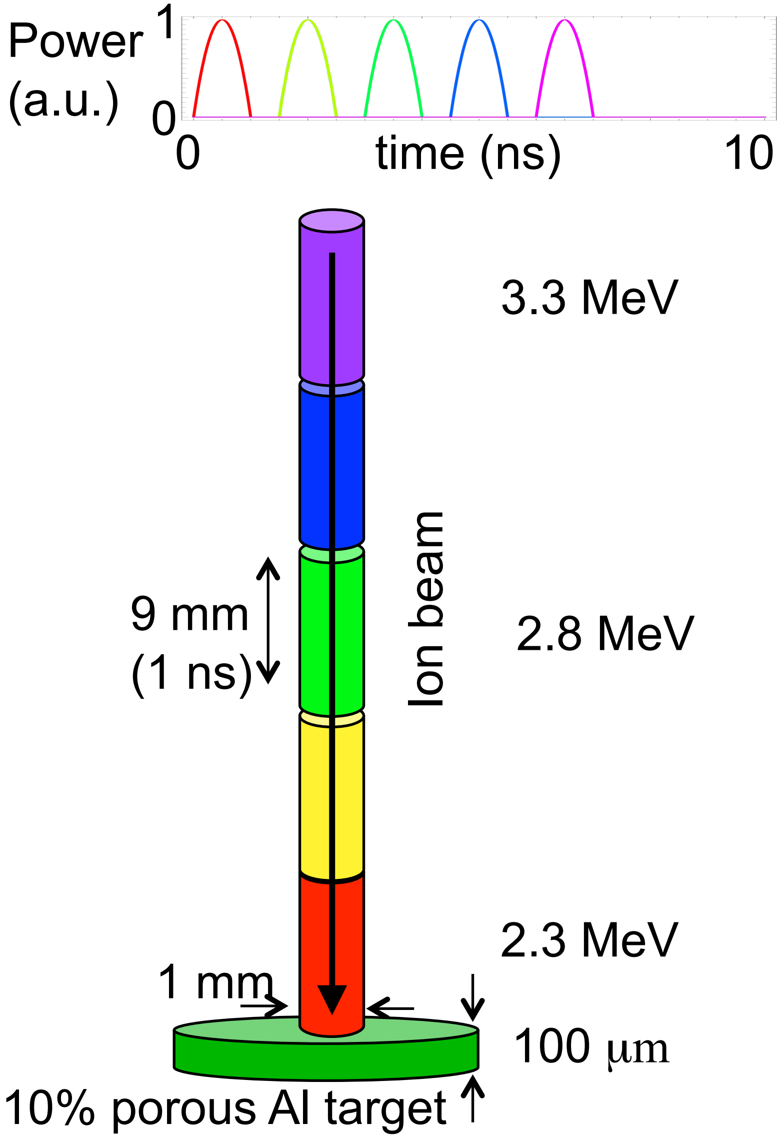
K.E. vs. time

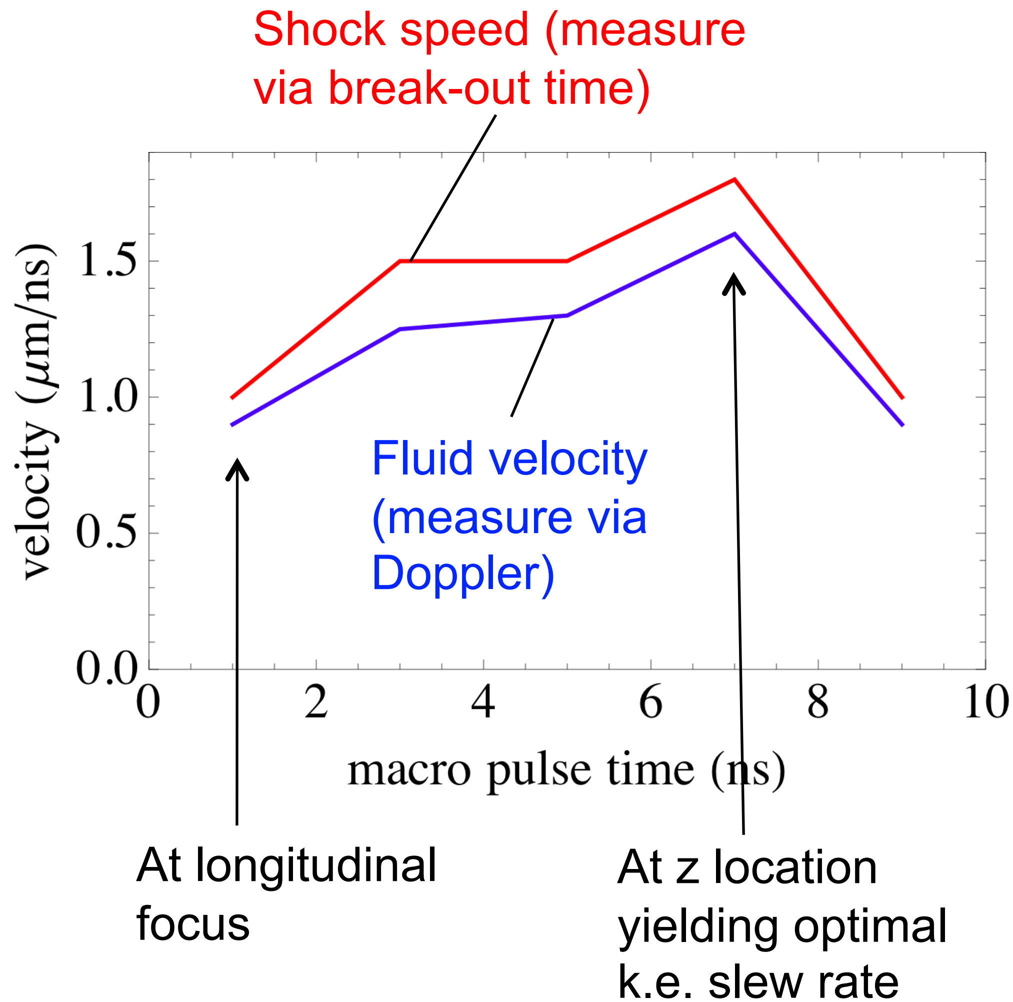


K.E. vs. time



Hydra results quantify the effects of positioning target upstream of the plane of best longitudinal focus





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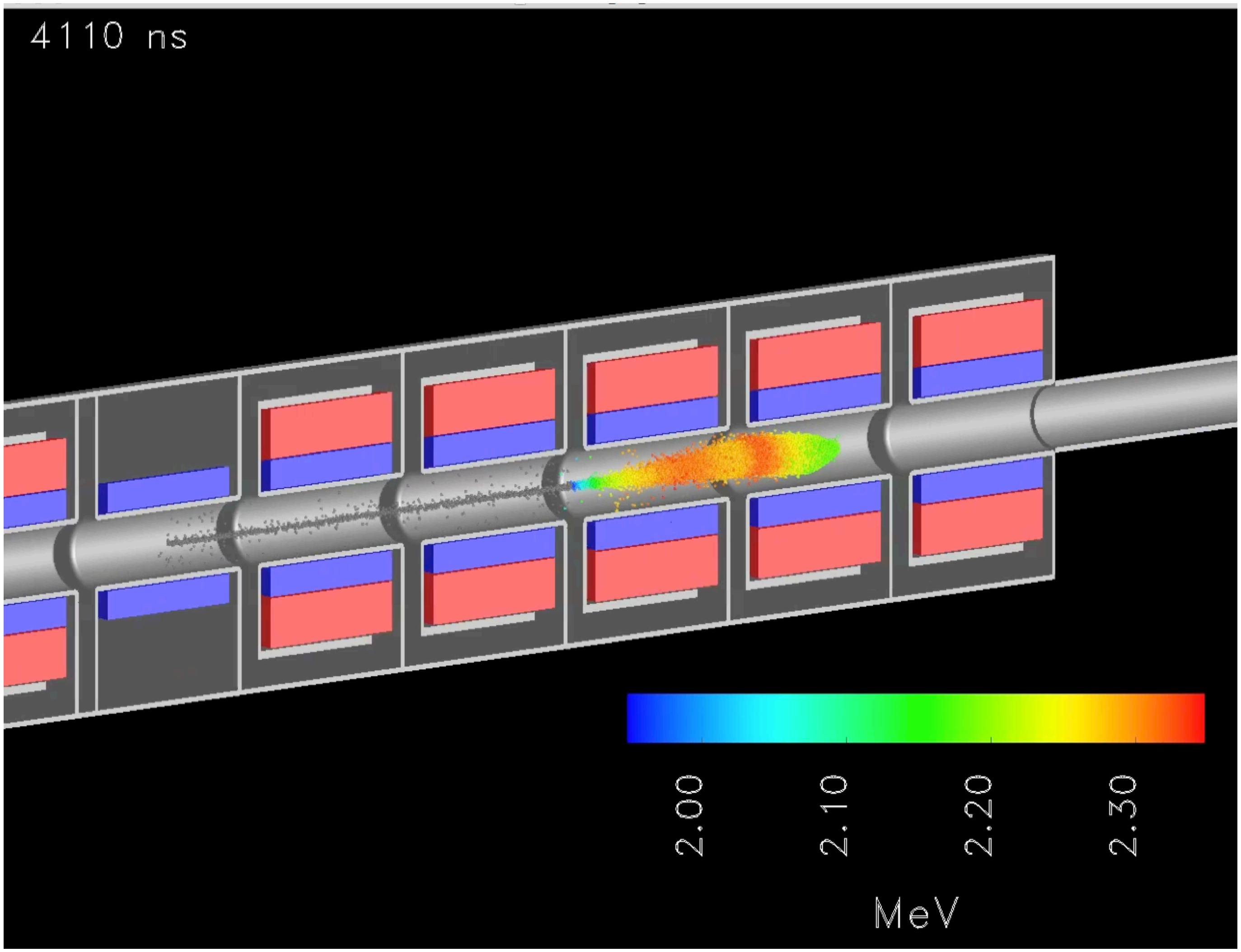
NDCX-II performance for typical cases in 12-21 cell configurations

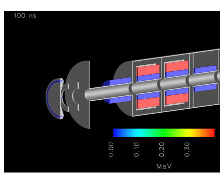
	NDCX-I (bunched beam)	NDCX-II			
		12-cell	15-cell	18-cell	21-cell
Ion species	K^+ (A=39)	Li^+ (A=7)	Li^+ (A=7)	Li^+ (A=7)	Li^+ (A=7)
Charge	15 nC	50 nC total 25 2xFWHM	50 nC total 25 2xFWHM	50 nC total 25 2xFWHM	50 nC total 30 2xFWHM
Ion kinetic energy	**0.3 MeV**	**1.2 MeV**	**1.7 MeV**	**2.4 MeV**	**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 = $\sqrt{2}$ 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
Max. central pressure in Al target		0.07 Mbar	0.18 Mbar	0.17 Mbar	0.23 Mbar
Max. central pressure in Au target		0.18 Mbar	0.48 Mbar	0.48 Mbar	0.64 Mbar

NDCX-II estimates are from (r,z) Warp runs (no misalignments), and assume uniform 1 mA/cm^2 emission, high-fidelity acceleration pulses and solenoid excitation, perfect neutralization in the drift line, and an 8-T final-focus solenoid; they also employ no fine energy correction (e.g., tuning the final tilt waveforms)

Video: Warp 3D simulation of 18-cell NDCX-II, including random offsets of solenoid ends by up to 2 mm (0.5 mm is nominal)



play video



A balanced IFE research program includes:

Target physics & design

Direct and indirect drive targets for power plant and for an intermediate target and accelerator physics facility

Symmetry requirements, beam pointing

Stability

Accelerator physics & driver design:

Multi-beam ion sources, injection, matching

Focusing elements: solenoids; magnetic & electric quadrupoles

Acceleration

Neutralized & un-neutralized drift compression

Halo formation and control

Achromatic focusing systems

Time dependent chromatic correction

Final focusing, reactor interface, design

Reactor and driver interface

Tritium breeding

Radiation shielding

Liquid protection

Enabling technology

Pulsed power

Insulators (e.g.: glassy ceramics, embedded rings)

Solenoid & quadrupole magnets

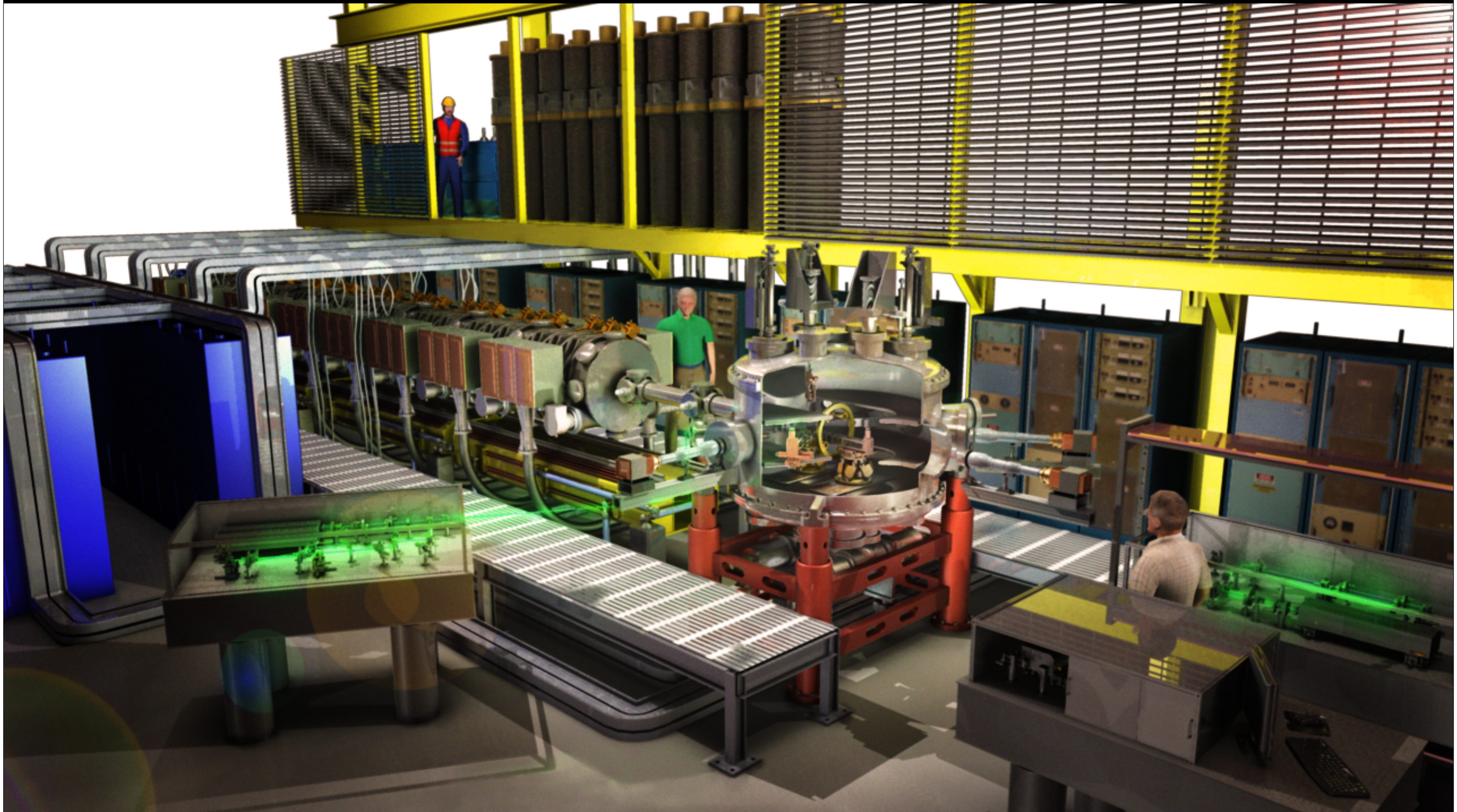
Superconducting materials (Nb3Sn)

Focusing arrays

Reactor materials and components

- Items in red are explored (to varying degrees) on the baseline NDCX-II accelerator.
- Items in green are to be explored via add-ons.

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



Heavy Ion Fusion Science Virtual National Laboratory

EXTRAS – NDCX-II misc

NDCX-II performance for typical cases in 12-21 cell configurations

	NDCX-I (bunched beam)	NDCX-II			
		12-cell (baseline)	15-cell	18-cell	21-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
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Max. central pressure in Au target		0.18 Mbar	0.48 Mbar	0.48 Mbar	0.64 Mbar

Caveats: these are from (r,z) Warp runs (no misalignments), and assume uniform 1 mA/cm^2 emission, front-end pulses that match the design, and perfect neutralization; they use only measured Blumlein waveforms

After injection, we seek to shorten the beam as soon as possible

- Equalize beam energy after injection -- then --
- Compress longitudinally before main acceleration
  - “non-neutral drift compression”
  - requires a large velocity “tilt” $v_z(z)$ ~ linear in z
- The beam profile’s evolution is determined by:
  - Optimized voltage waveforms in acceleration gaps
  - space charge effects
- Goals are:
  - Rapid achievement of transit times across gaps < 70 ==> can then use 200-kV pulses from ATA Blumleins
  - Smooth beam profile

After the initial compression, the main acceleration is applied using 200-250 kV Blumlein pulses

- Rapid inward motion in beam frame is required to get below 70 ns
- Space charge ultimately inhibits this compression
- Beam length stays constant (in longer machines it grows) while we apply:
  - additional acceleration via flat pulses
  - confinement via ramped (“triangular”) pulses
- The final few gaps apply the “exit tilt” needed for neutralized drift compression

EXTRAS – ASP code

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

- Follows (z,v_z) phase space using a few hundred particles ("slices")
- Accumulates line charge density $\lambda(z)$ on a grid via particle-in-cell
- Space-charge field via Poisson equation with finite-radius correction term

$$\frac{\partial^2 \phi(z)}{\partial z^2} - k_\perp^2 \phi(z) = -\frac{\lambda(z)}{\epsilon_0 \pi r_{\mathrm{beam}}^2} \; ; \qquad E_z(z) = -\frac{\partial \phi(z)}{\partial z}$$

$$k_\perp^2 = \frac{4}{g_0 r_{\mathrm{beam}}^2} \; ; \qquad g_0 = 2 \ln \frac{r_{\mathrm{wall}}}{r_{\mathrm{beam}}} + \alpha$$

Here, α is between 0 (incompressible beam) and ½ (constant radius 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
- Optimization loops for waveforms & timings, dipole strengths (steering)
- Interactive (Python language with Fortran for intensive parts)

The field model in ASP yields the correct long-wavelength limit

- For hard-edged beam of radius r_b in pipe of radius r_w , 1-D (radial) Poisson eqn gives:

$$\phi(r) = \frac{\lambda}{2\pi\epsilon_0} \begin{cases} \left[\frac{1}{2}\left(1 - \frac{r^2}{r_b^2}\right) + \ln\frac{r_w}{r_b}\right], & r < r_b \\ \ln\left(\frac{r_w}{r}\right), & r_b \le r < r_w \end{cases}$$

- The axial electric field within the beam is:

$$E_z(r,z) = -\frac{1}{2\pi\epsilon_0}\left\{\left[\frac{1}{2}\left(1 - \frac{r^2}{r_b^2}\right) + \ln\frac{r_w}{r_b}\right]\frac{\partial\lambda(z)}{\partial z} - \left[1 - \frac{r^2}{r_b^2}\right]\frac{\lambda(z)}{r_b}\frac{\partial r_b}{\partial z}\right\}$$

- For a space-charge-dominated beam in a uniform transport line, $\lambda/r_b^2 \approx$ const.; find:

$$E_z(r,z) = -\frac{g_{\text{scd}}}{4\pi\epsilon_0}\frac{\partial\lambda(z)}{\partial z} \; ; \qquad g_{\text{scd}} = 2\ln\frac{r_w}{r_b}$$

- For an emittance-dominated beam $r_b \approx$ const.; average over beam cross-section, find:

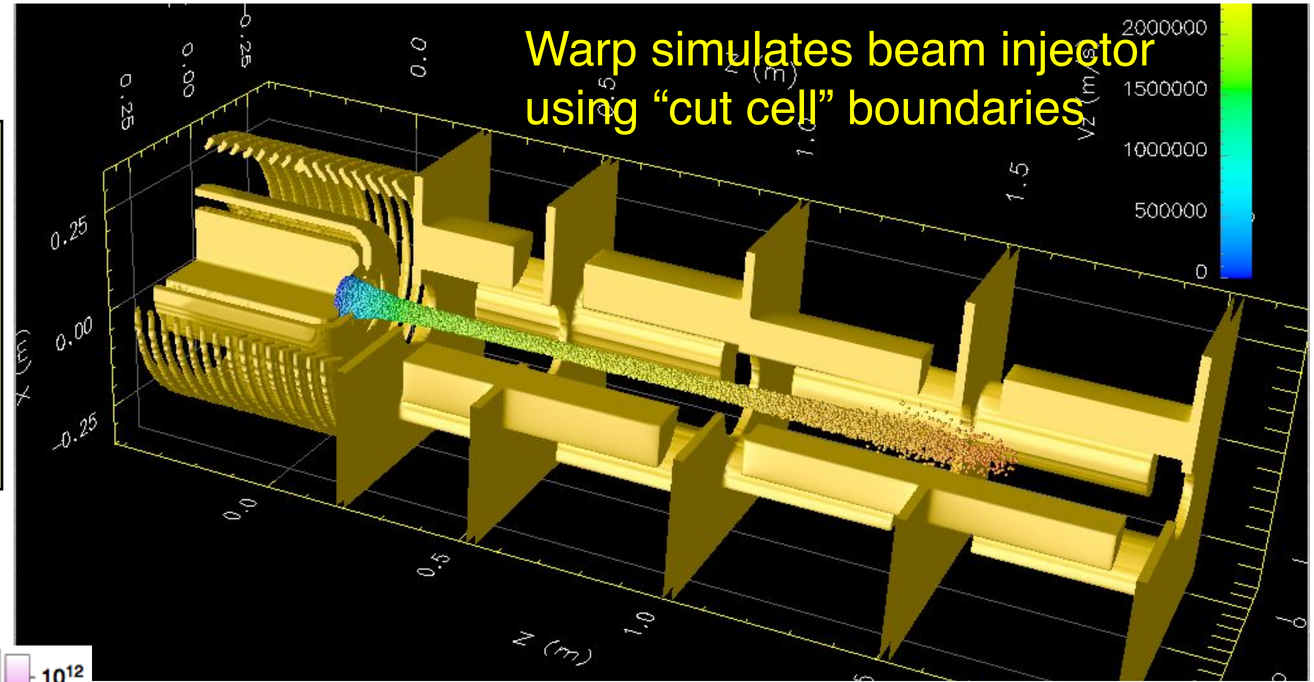
$$\langle E_z\rangle(z) = -\frac{g_{\text{ed}}}{4\pi\epsilon_0}\frac{\partial\lambda(z)}{\partial z} \; ; \qquad g_{\text{ed}} = 2\ln\frac{r_w}{r_b} + \frac{1}{2}$$

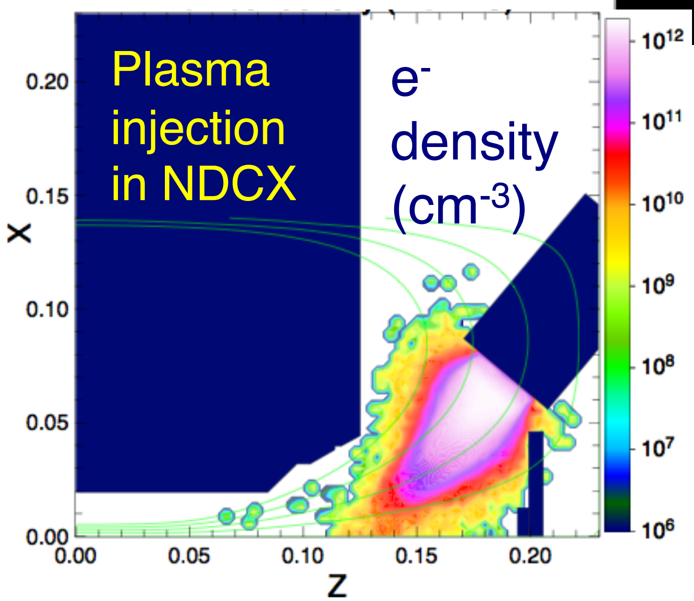
- The ASP field equation limits to such a "g-factor" model when the $k_\perp^2$ term dominates
- In NDCX-II we have a space-charge-dominated beam, but we adjust the solenoid strengths to keep r_b more nearly constant; $g_0 = 2\ln(r_w/r_b) + \alpha \; ; \;\; 0 < \alpha < 1/2$
- In practice we tune α to obtain agreement with Warp results

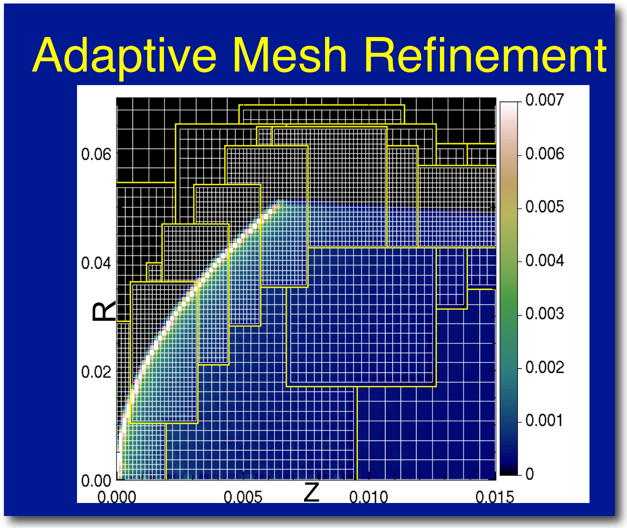
EXTRAS – Warp code

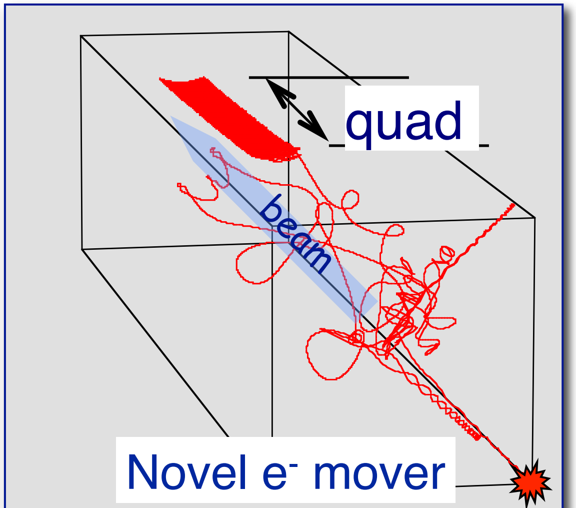
The HIF program has developed advanced methods to enable efficient simulation of beam and plasma systems

With new electron mover and mesh refinement, run time in an electron cloud problem was reduced from 3 processor-months to 3 processor-days



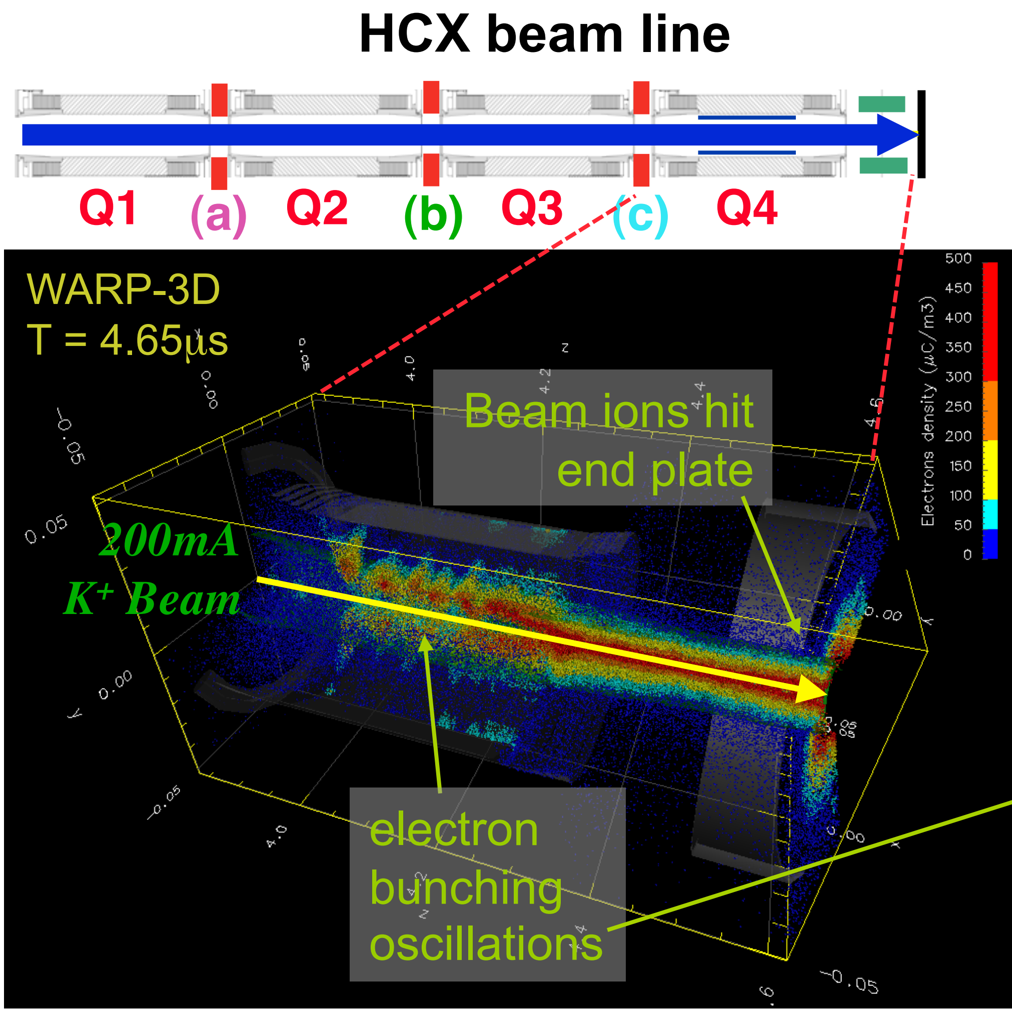


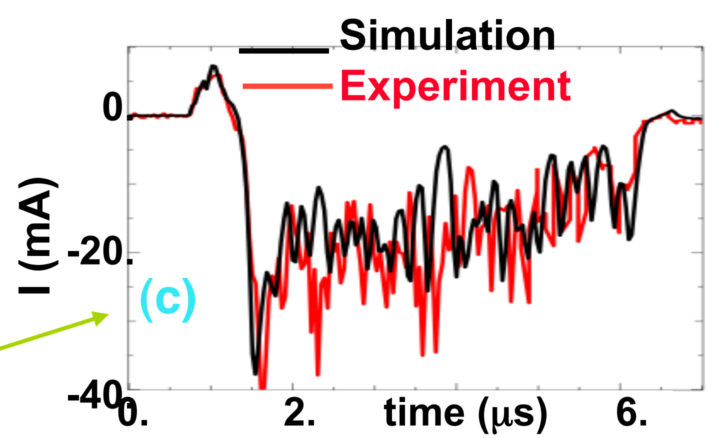




The Warp code includes e-cloud & gas models; here, we modeled and tested deliberate e-cloud generation on HCX

6-MHz oscillations were seen first in simulations; then they were sought and measured at station (c) in experiments.

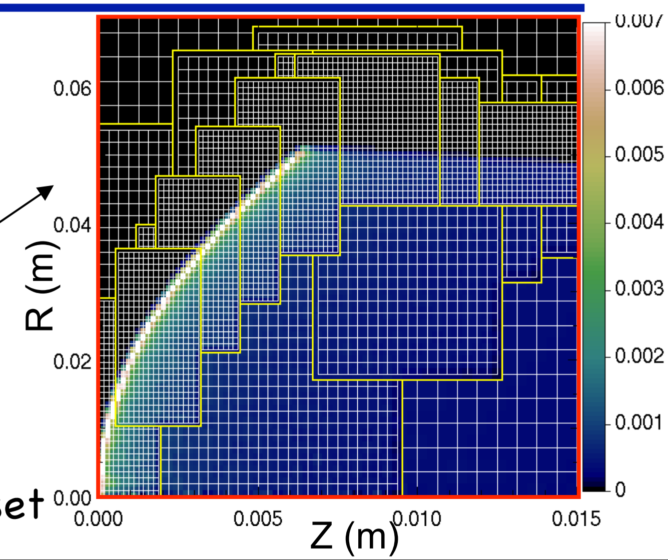


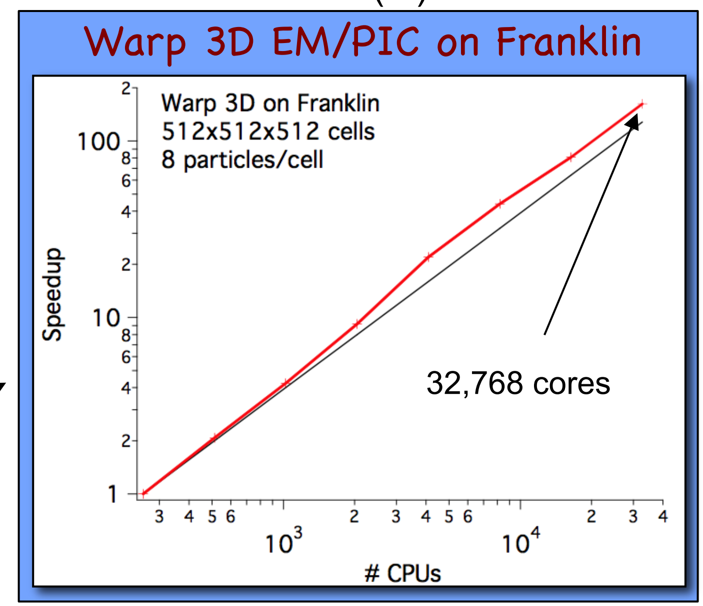


The Heavy Ion Fusion Science
Virtual National Laboratory

Warp: a parallel framework combining features of plasma (Particle-In-Cell) and accelerator codes

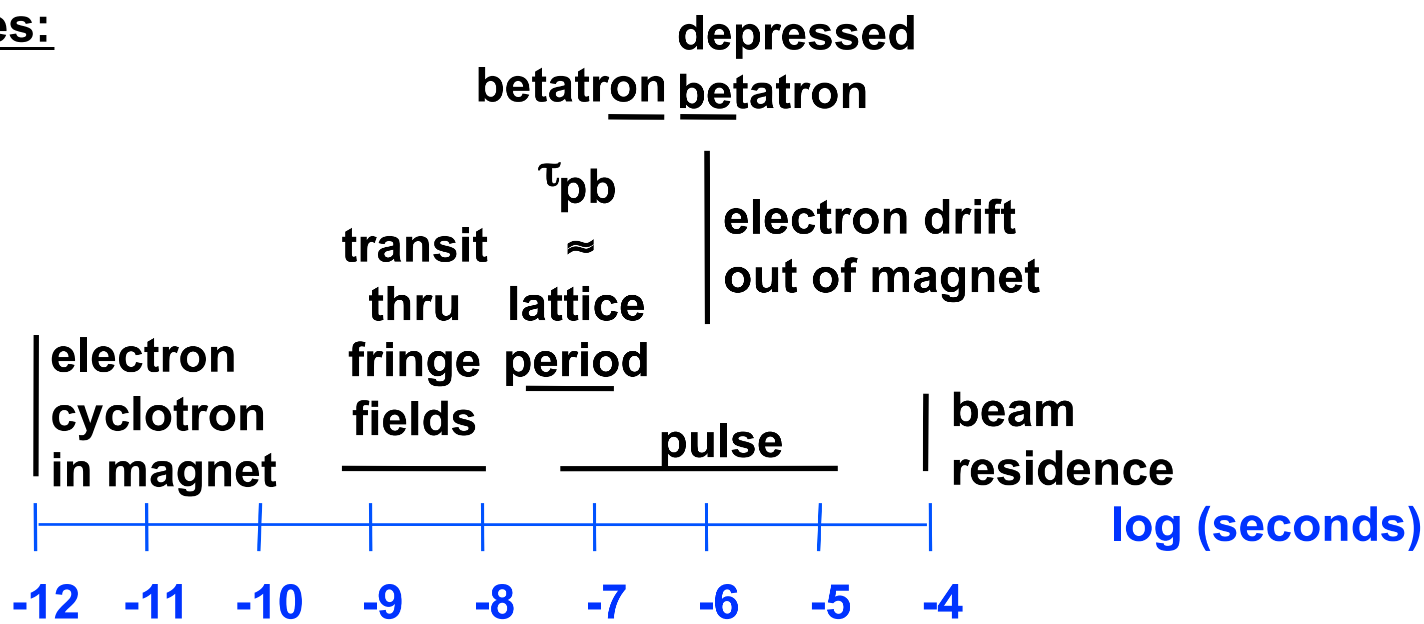
- **Geometry:** 3D (x,y,z), 2-1/2D (x,y), (x,z) or axisym. (r,z)
- **Python and Fortran:** "steerable," input decks are programs
- **Field solvers:** Electrostatic - FFT, multigrid; implicit; AMR
  Electromagnetic - Yee, Cole-Kark.; PML; AMR
- **Boundaries:** "cut-cell" --- no restriction to "Legos"
- **Applied fields:** magnets, electrodes, acceleration gaps, user-set
- **Bends:** "warped" coordinates; no "reference orbit"
- **Particle movers:** Energy- or momentum-conserving; Boris, large time step "drift-Lorentz", novel relativistic Leapfrog
- **Surface/volume physics:** secondary e^- & photo-e^- emission, gas emission/tracking/ionization, time-dependent space-charge-limited emission
- **Parallel:** MPI (1, 2 and 3D domain decomposition)



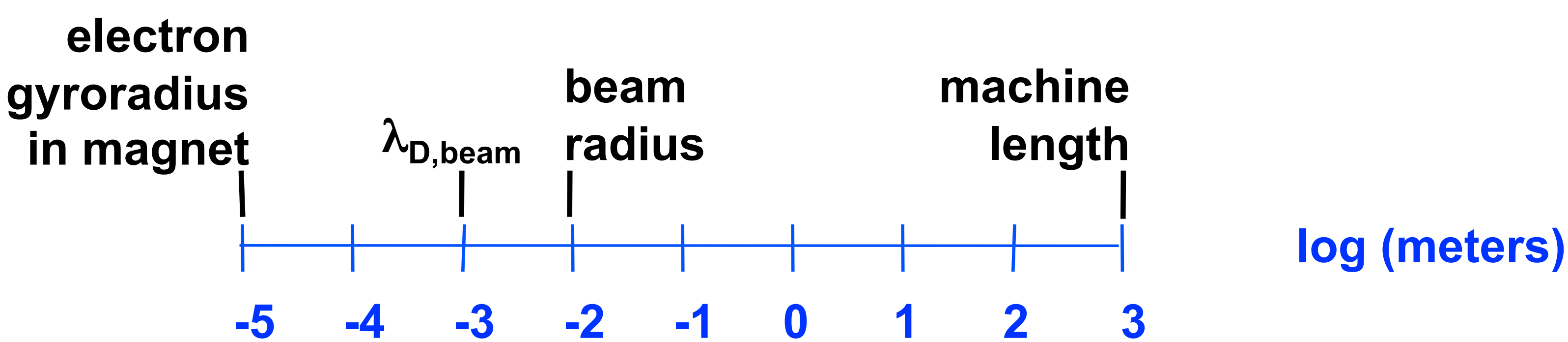


Time and length scales span a wide range

Time scales:

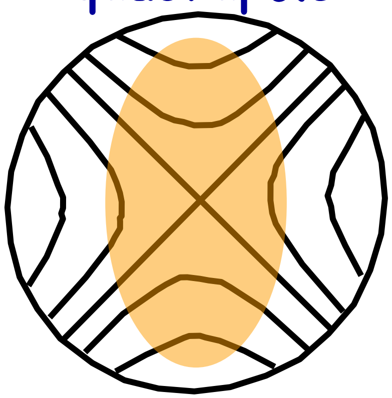


Length scales:



New "Drift-Lorentz" mover relaxes the problem of short electron timescales in magnetic field*

Magnetic quadrupole



Problem: Electron gyro timescale

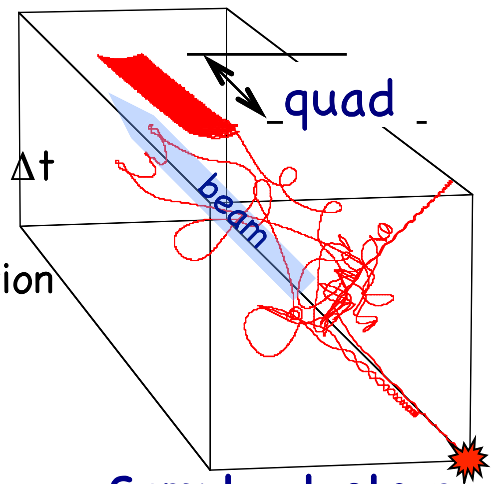
<< other timescales of interest

⇒ brute-force integration <u>very</u> slow due to small Δt

Solution*: Interpolation between full-particle dynamics ("Boris mover") and drift kinetics (motion along B plus drifts)

$$\mathbf{v}_{eff} = \mathbf{b}(\mathbf{b} \cdot \mathbf{v}_L) + \alpha \mathbf{v}_{L,\perp} + (1-\alpha)\mathbf{v}_d$$

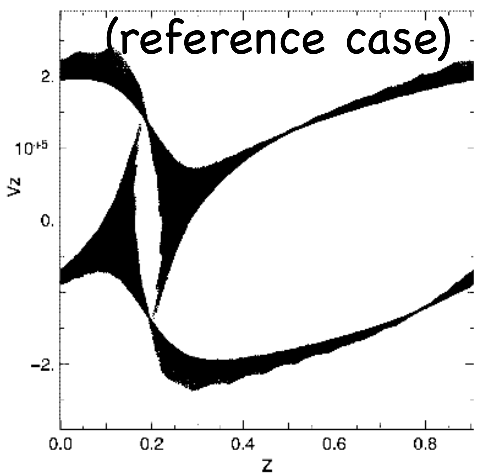
correct gyroradius with $\alpha = 1/[1+(\omega_c \delta t/2)^2]^{1/2}$



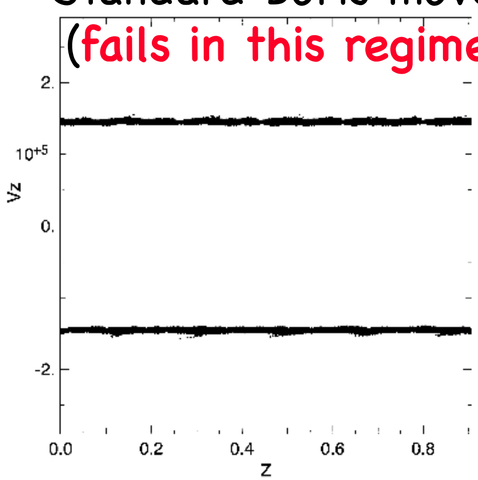
Sample electron motion in a quad

Test: Magnetized two-stream instability

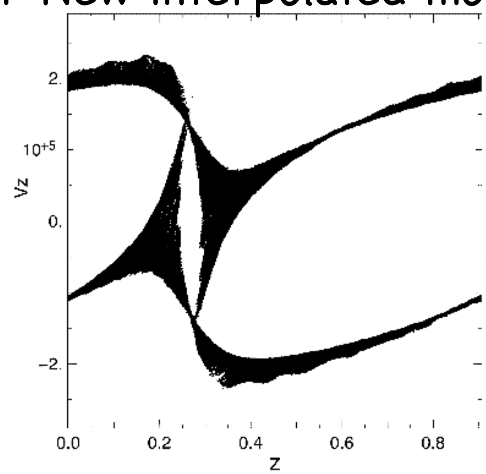
small δt=0.25/ω_c Standard Boris mover (reference case)



large δt=5./ω_c Standard Boris mover (fails in this regime)



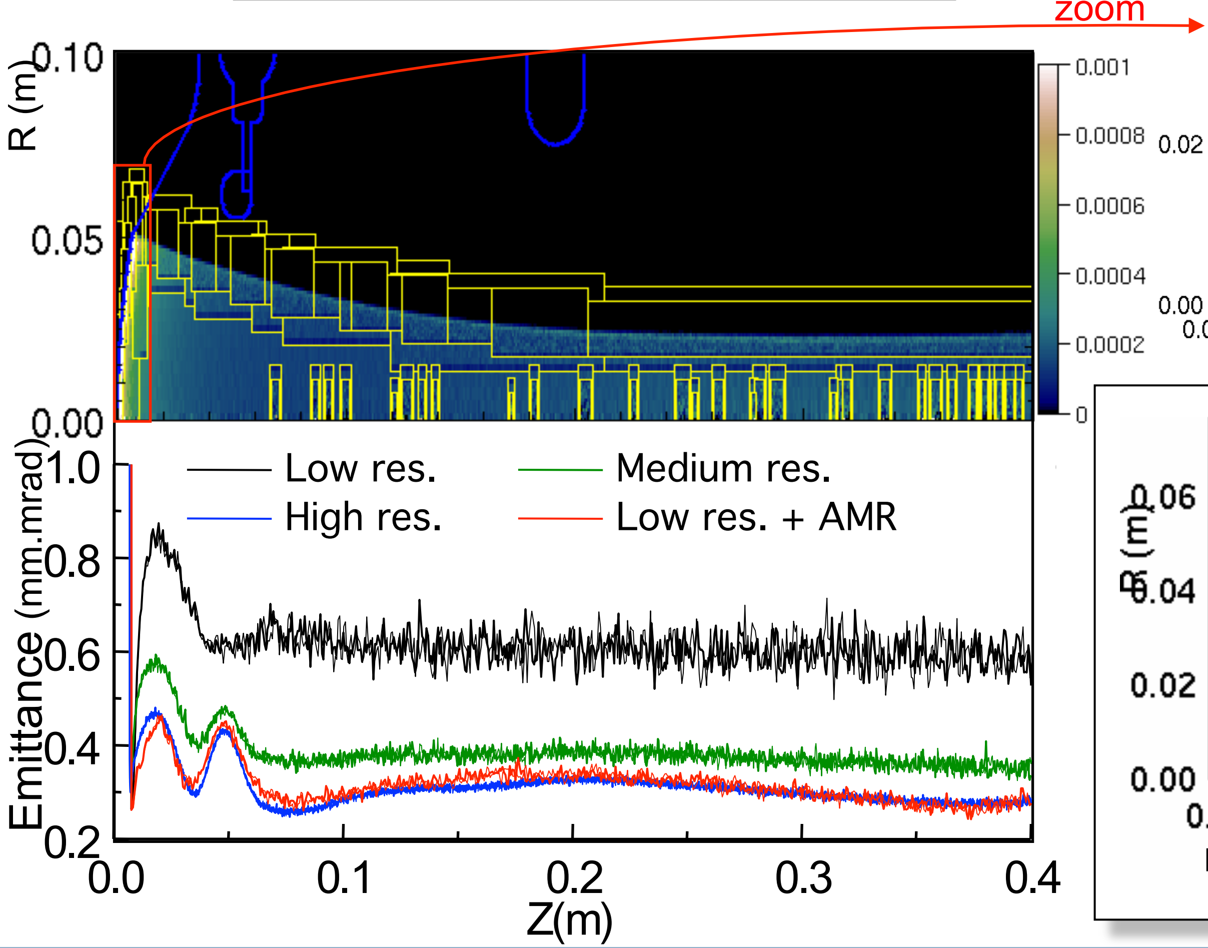
large δt=5./ω_c New interpolated mover

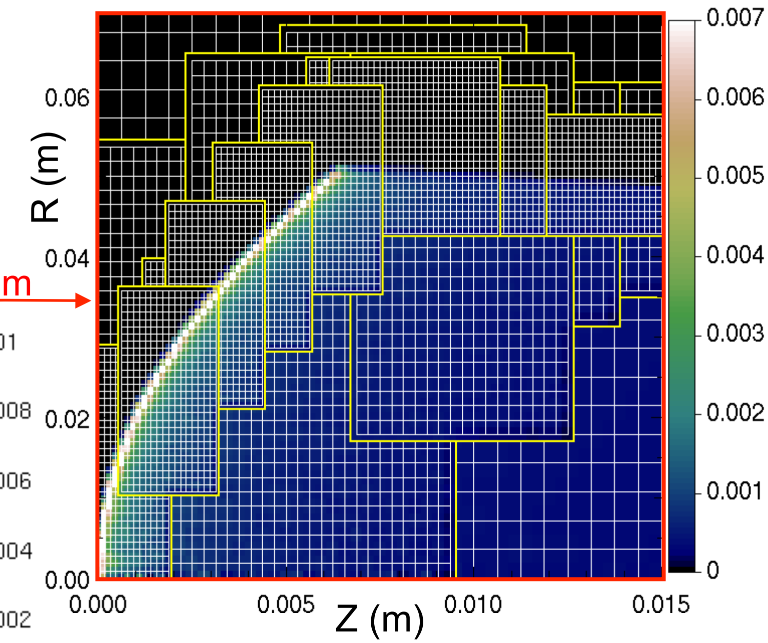


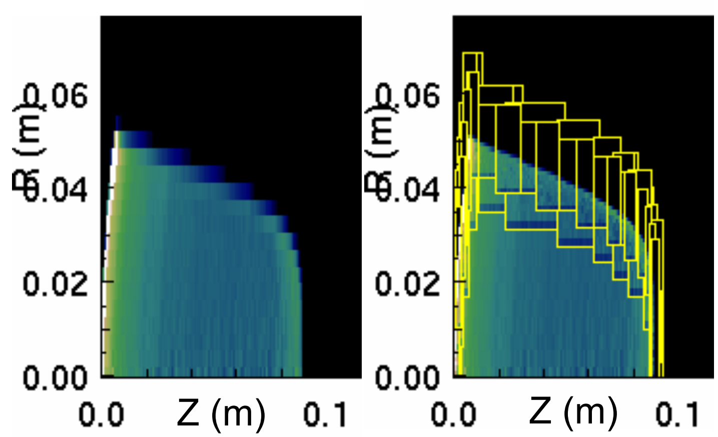
*R. Cohen et. al., *Phys. Plasmas*, May 2005

Electrostatic AMR simulation of ion source with the PIC code Warp: speedup x10

Run	Grid size	Nb particles
Low res.	56x640	~1M
Medium res.	112x1280	~4M
High res.	224x2560	~16M
Low res. + AMR	56x640	~1M

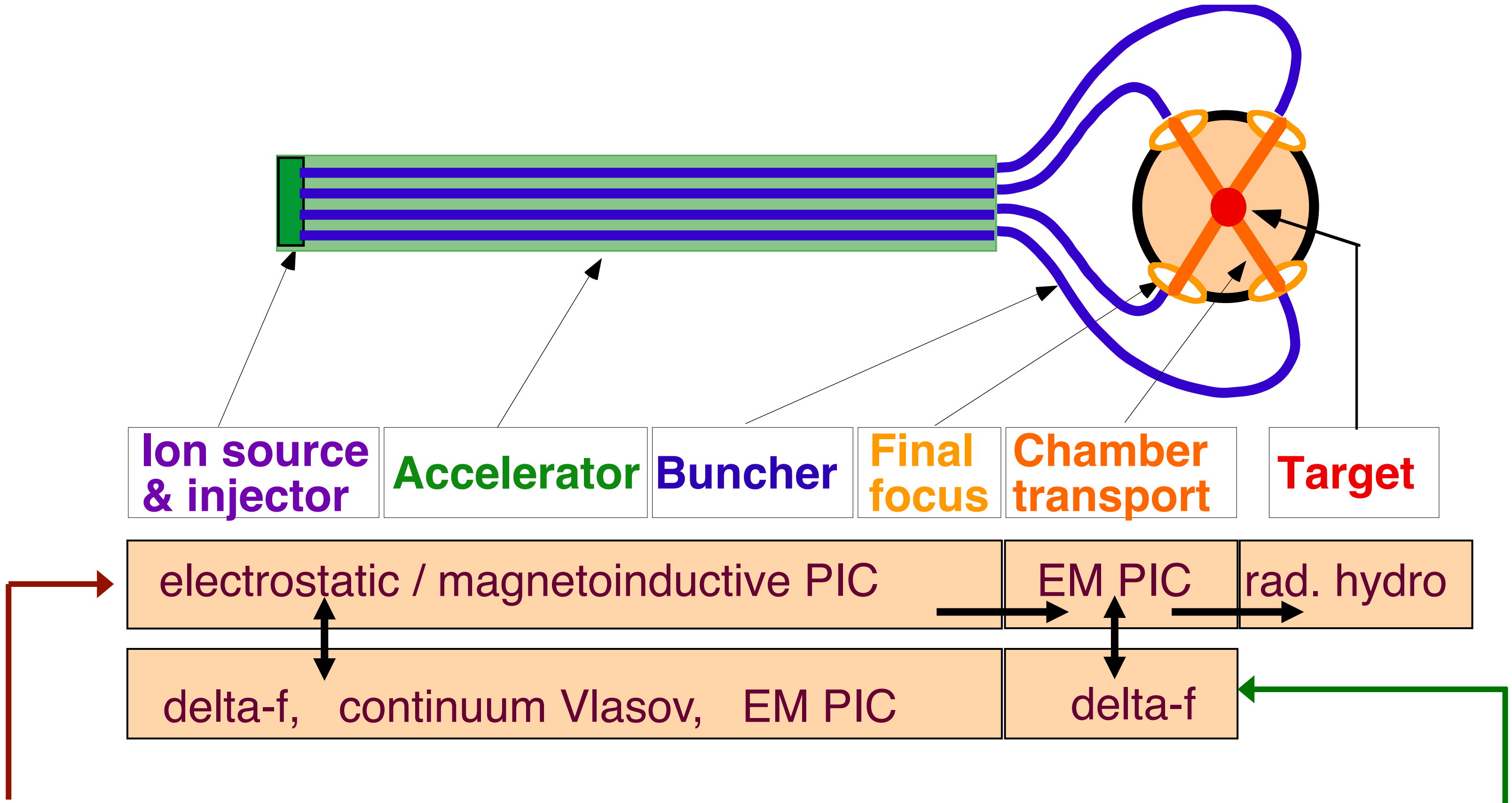






Refinement of gradients: emitting area, beam edge and front.

Approach to end-to-end simulation of a fusion system



"main sequence" tracks beam ions consistently along entire system

instabilities, halo, electrons, ... are studied via coupled detailed models

Warp

- **Warp is a state-of-the-art 3-D parallel multi-physics code and framework**
  - *modeling of beams in accelerators, plasmas, laser-plasma systems, non-neutral plasma traps, sources, etc.*
  - *unique features: ES/EM solvers, cut-cells, AMR, particles pushers, python interface, etc.*
- **Contribution to projects**
  - **HIFS-VNL (LBNL,LLNL,PPPL)**: work-horse code; design and support expts.
  - **VENUS ion source (LBNL):** modeling of beam transport
  - **LOASIS (LBNL):** modeling of LWFA in a boosted frame
  - **FEL/CSR (LBNL) :** modeling of free e- lasers & coherent synch. radiation in boosted frame
  - **Anti H- trap (LBNL/U. Berkeley):** simulation of model of anti H- trap
  - **U. Maryland:** modeling of UMER sources and beam transport; teaching
  - **Ferroelectric plasma source (Technion, U. Maryland)**: modeling of source
  - **Fast ignition (LLNL):** modeling physics of filamentation
  - **E-cloud for HEP (LHC, SPS, ILC, Cesr-TA, FNAL-MI):** see slide on Warp-Posinst
  - **Laser Isotope Separation (LLNL):** now defunct
  - **PLIA (CU Hong Kong)**: modeling of beam transport in pulsed line ion accelerator
  - **Laser driven ions source (TU Darmstadt)**: modeling of source
- **Benchmarking**
  - Heavily benchmarked against various experiments: MBE4, ESQ ion source, HCX, multibeamlet ion source, UMER, NDCXI, etc.; codes: IGUN, LSP; theory: beam transport and plasma analytic theory