MODELING ELECTRON CLOUD EFFECTS IN HEAVY ION ACCELERATORS*

R.H. Cohen[1,2], A. Azevedo[3], A. Friedman[1,2], M.A. Furman[3], S.M. Lund[1,2], A.W. Molvik[1,2], P. Stoltz[4], J.-L. Vay[1,2], S. Veitzer[4]

[1] *HIF-VNL,* [2] *LLNL,* [3] *LBNL,* [4] *TechX Corp*

Presented at 2004 Electron Cloud Workshop
Napa, CA, USA
April 21, 2004

* UCRL-CONF-203654
Work performed for U.S. D.O.E. by U.C. LLNL under contract W7405-ENG-48 and by U.C. LBNL under contract DE-AC03-76F00098

OUTLINE

- Distinguishing features of ecloud issues for HIF
- Our plan for self-consistent modeling
- Example with wall electron sources
- Electron effects on ions: simulations with specified electron distributions
- Preliminary results for averaged electron dynamics
- Summary

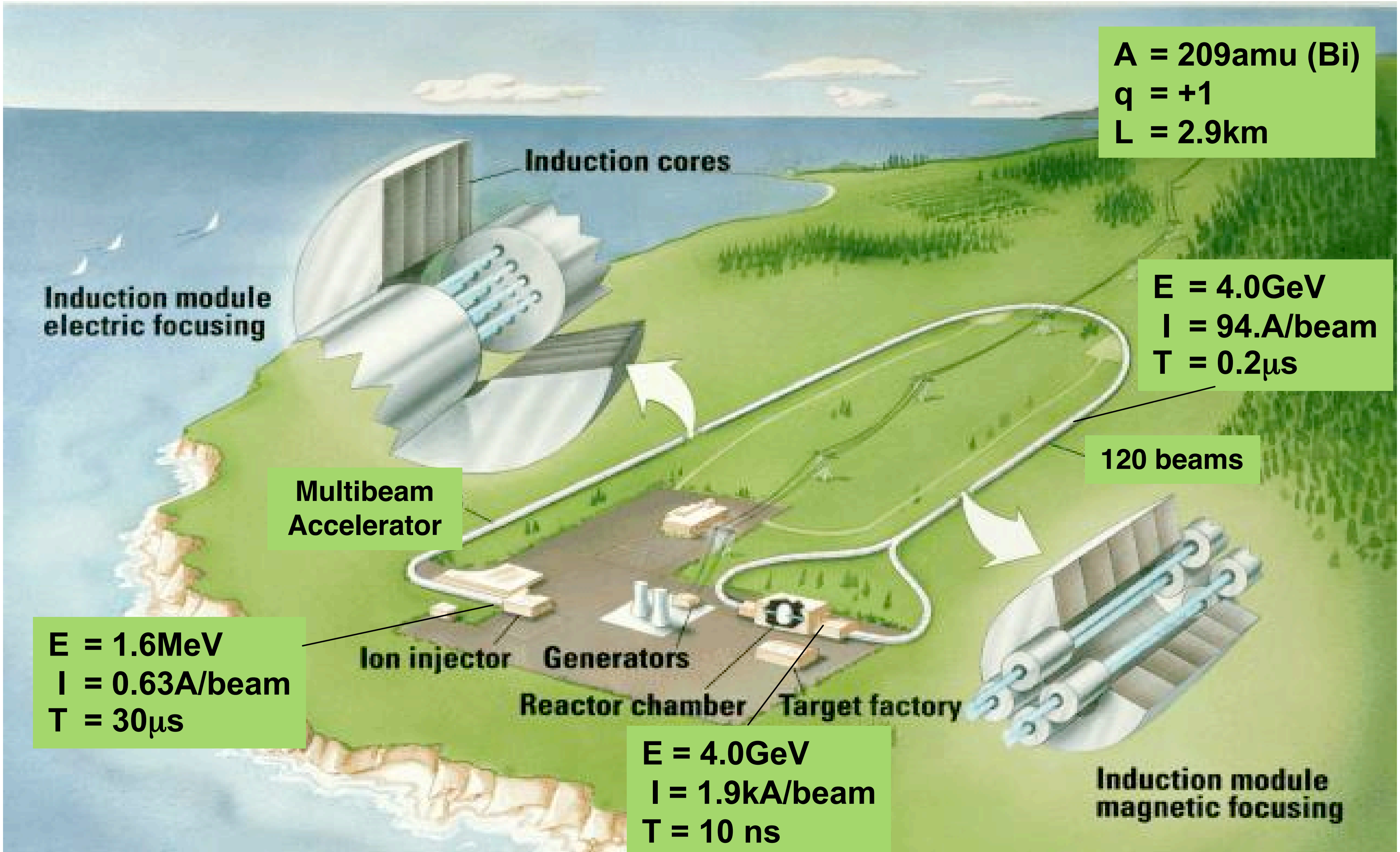
Related papers:

Molvik et al (Monday p.m.)

Vay et al (Tues. p.m.)

Stoltz et al (next paper)

Artist's Conception of an HIF Power Plant on a few km^2 site



HIF accelerators have distinguishing features that impact electron cloud issues

Compared to other accelerator applications:

- Many common issues and concerns, but also application-specific features
- Distinguishing aspects of HIF accelerators (U.S. main line with magnetic quadrupole focusing):
  - Linac with high line charge density
  - Induction accelerator --
    - hard to clean beam pipe ⇒ large neutral emission coefficient at pipe wall ($\gtrsim 10^4$ per lost ion)
    - Beam pipe only in quad magnets ⇒ scrape-off only in quads
  - Economic mandate to maximally fill beam pipe
  - Large fraction of length occupied by quadrupoles (>50% at injector end)
  - Long(ish) pulses -- multi-μs at injector end

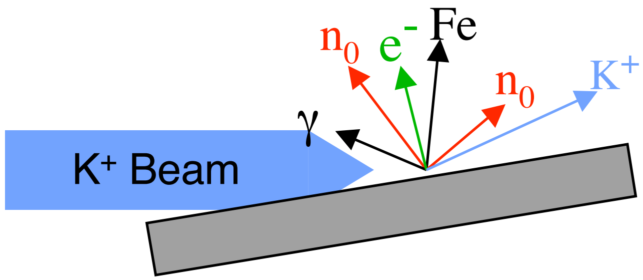
Consequences 1

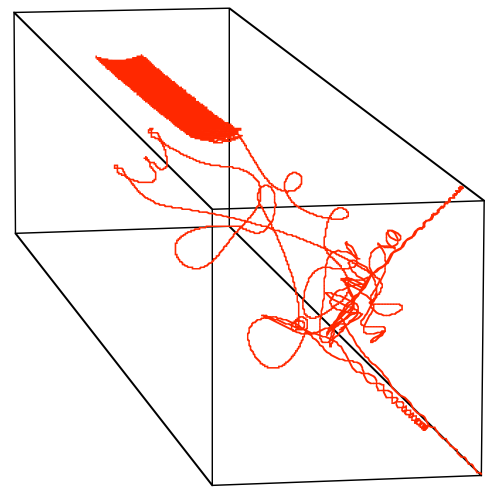
- Linac, so multiturn resonance not an issue
  - But long pulse ⇒ still instability if e-e SEY > 1
- Electrons largely confined to the quadrupole in which they are born, and electron density smaller in gaps than in quads; consequences of:
  - Beam pipe only in quads; strongly magnetized electrons
  - Time to drift out of a quad ~ pulse durations
  - Accelerating gaps between quads, which enable electrons to overcome space charge potential

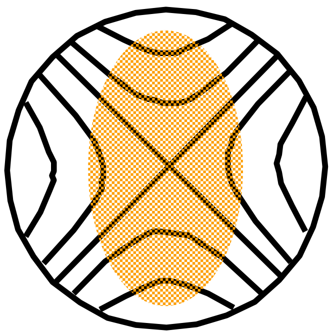
  Important implications for potential instabilities.
- Filling pipe as much as possible ⇒ ion scrape-off major source of electrons

Consequences 2: Electrons from gas released at walls in quads dominate

- e^- from ionization of neutrals released from walls dominates for long (multi-μs) pulses.
  - Born trapped by beam potential
    - Bounce radially
    - Drift axially
    - Acquire enough energy in gap to escape
    - Hence τ_e ~ time to drift through 1 quad
- For shorter pulses: wall-born electrons from ion bombardment
  - Nominal lifetime 1 transit (during beam flattop)
  - e^- from scrapeoff of beam ions: mainly on field lines that stay close to wall.
  - For small fraction born on field lines that penetrate deep into interior, collisionless pitch-angle scattering (nonadiabaticity) can make lifetime much longer





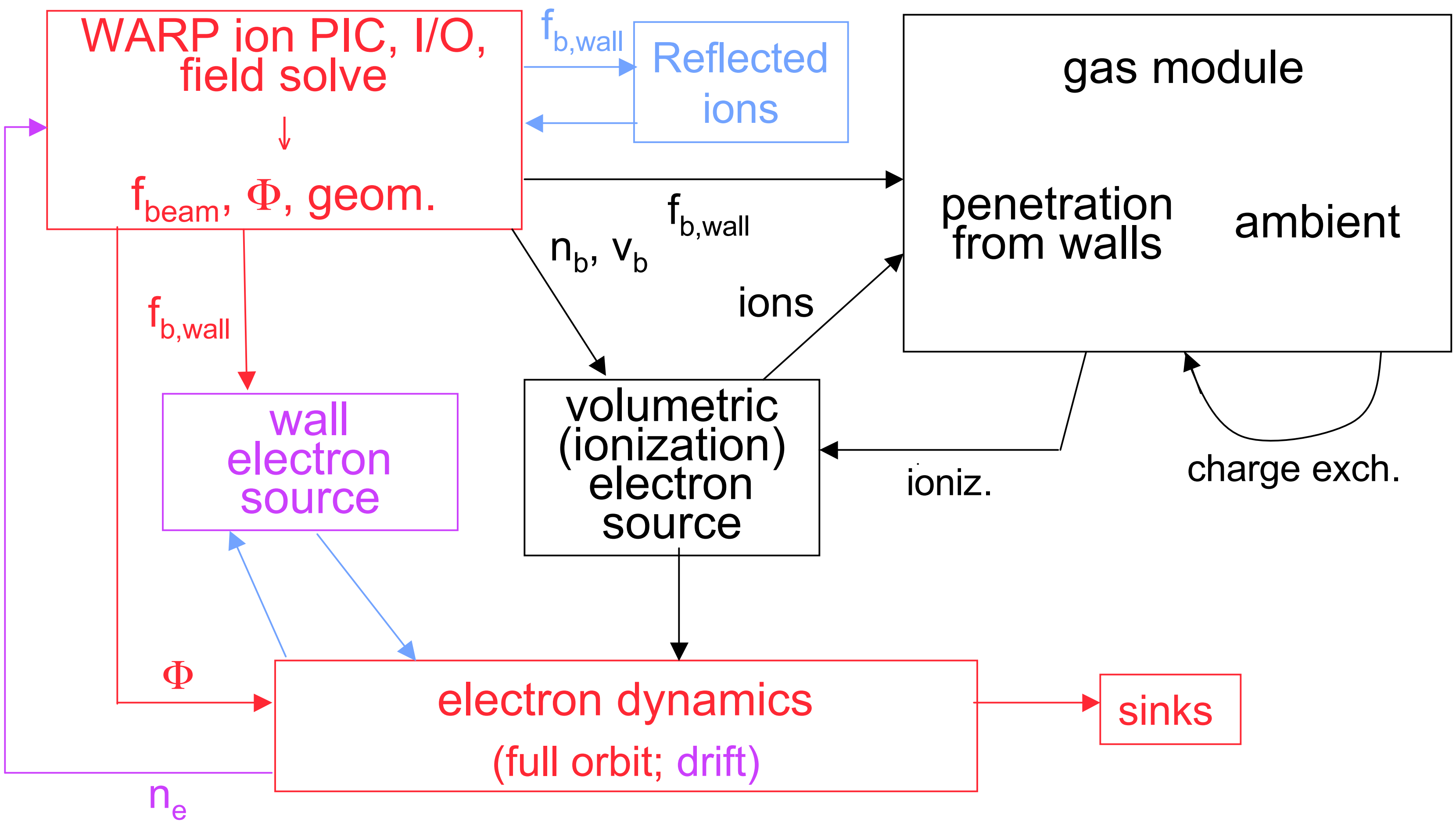


Consequences 3: we absolutely need to do e-cloud generation + e, i dynamics self-consistently

- Because of size of beam-scrape-off sources and long pulse, electron-ion interaction affects electron sources
- Especially challenging for us because
  - Timescales: need to deal with electrons in and between quads, so must deal with electron cyclotron motion yet follow ion dynamics (can't analytically integrate the cyclotron motion)
  - Variety of e-cloud sources
- But – it may be that other e-cloud applications will also have this same need and face the same challenges

Toward a self-consistent model of electron effects

- Plan for self-consistent electron physics modules for WARP



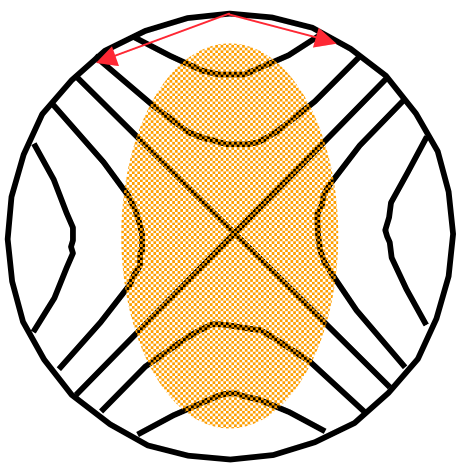
- Key: operational; implemented, testing; partially implemented; offline development

Example of current capability: wall-born electrons from primary and secondary ion bombardment

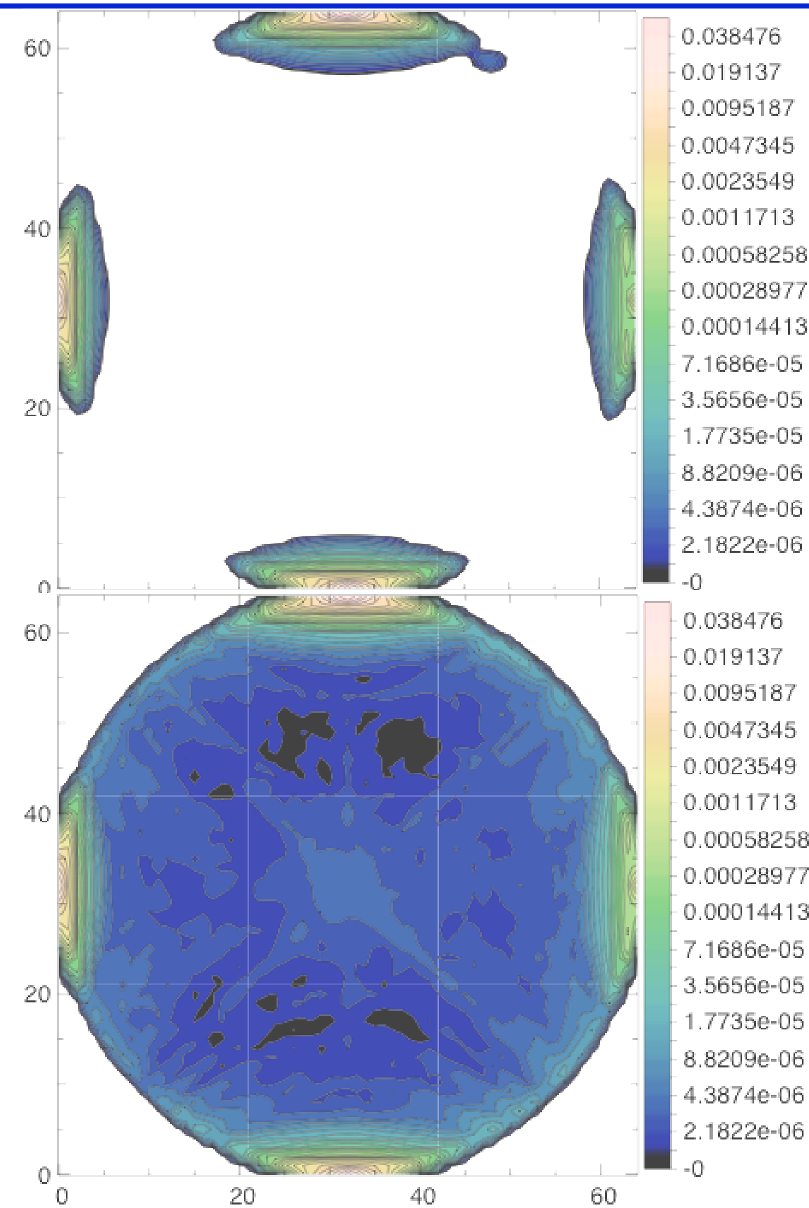
- WARP ion slice simulation, 400,000 ions
  - 100 lattice-period transport system (no acceleration)
  - Misaligned magnets (500 μm) to exaggerate beam scrapeoff
- Gather data for ions impacting wall (6282 ions), and calculate:
  - Electrons produced (from simple fit to Molvik et al data)
  - Scattered ion population (3629 ions), from TRIM Monte-Carlo code
- Follow the scattered ions in 3-D Warp until they next impact wall.
- Calculate electrons produced by those ions
- Follow dynamics of electrons produced by primary and scattered ion impacts with 3-D WARP; accumulate electron charge density

Calculation of n_e from wall-born electrons shows importance of following scattered ions

- Full-orbit calculations of electrons born near wall from impact of lost beam ions
  - Based on initial ion-wall impacts: cloud confined to wall near beam ellipse tips



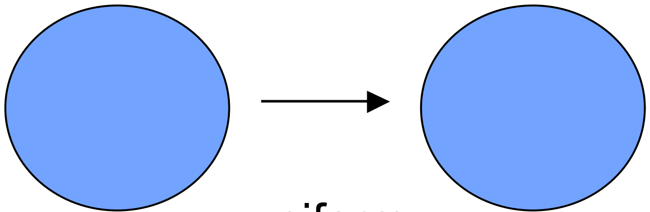
  - Dramatic difference if we follow scattered ions and add in the electrons THEY produce



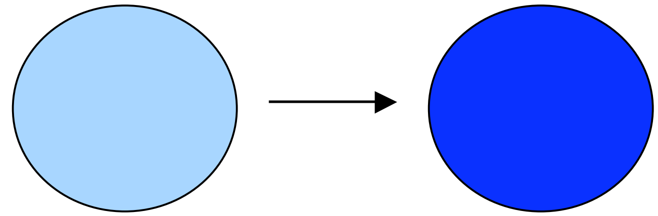
Ion simulations with legislated electron clouds show level of acceptable density and highlight areas for concern

- Perform ion simulations with legislated negative charge distributions to mock up electrons
- All choices have constant parameters within a quad, but variable from quad to quad:
  - Const n_e
  - Random cloud amplitude variations
  - Sinusoidal cloud variations, with period chosen to match a beam natural mode
    - Breathing (amplitude or shape)
    - Centroid oscillations (dipole mode)
    - Elliptical distortion oscillations (quadrupole mode)
  - Types of electron cloud variations studied (in all cases the perturbation is axially constant within a quadrupole, and varies from quad to quad):

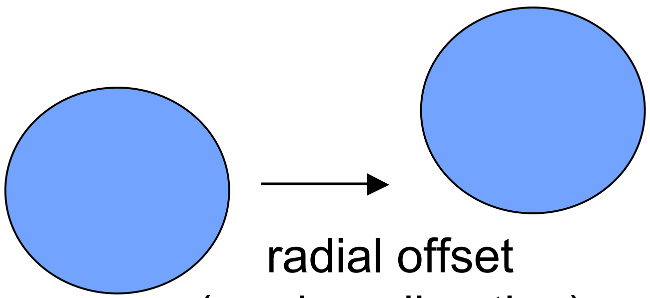
Types of electron cloud perturbations specified



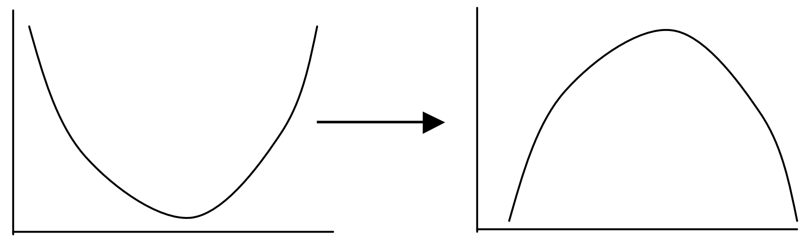
uniform



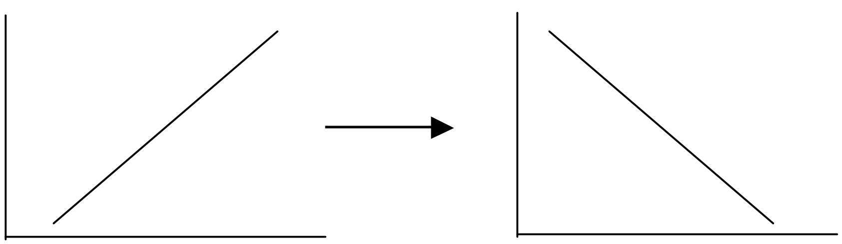
amplitude



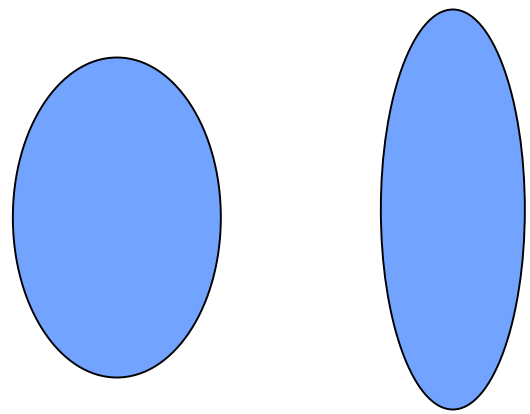
radial offset
(random direction)



radial shape variation

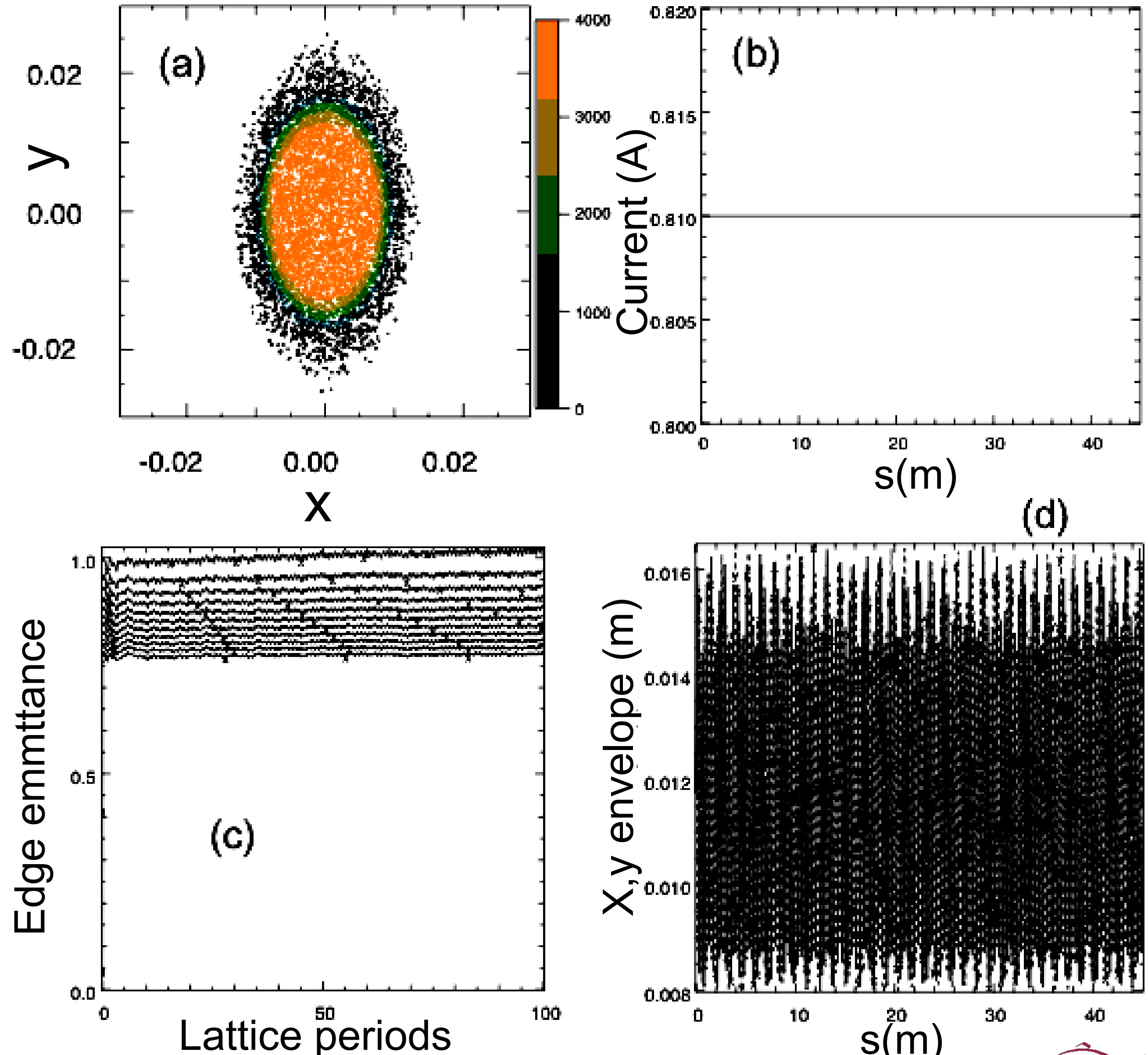


ramp (rotating)

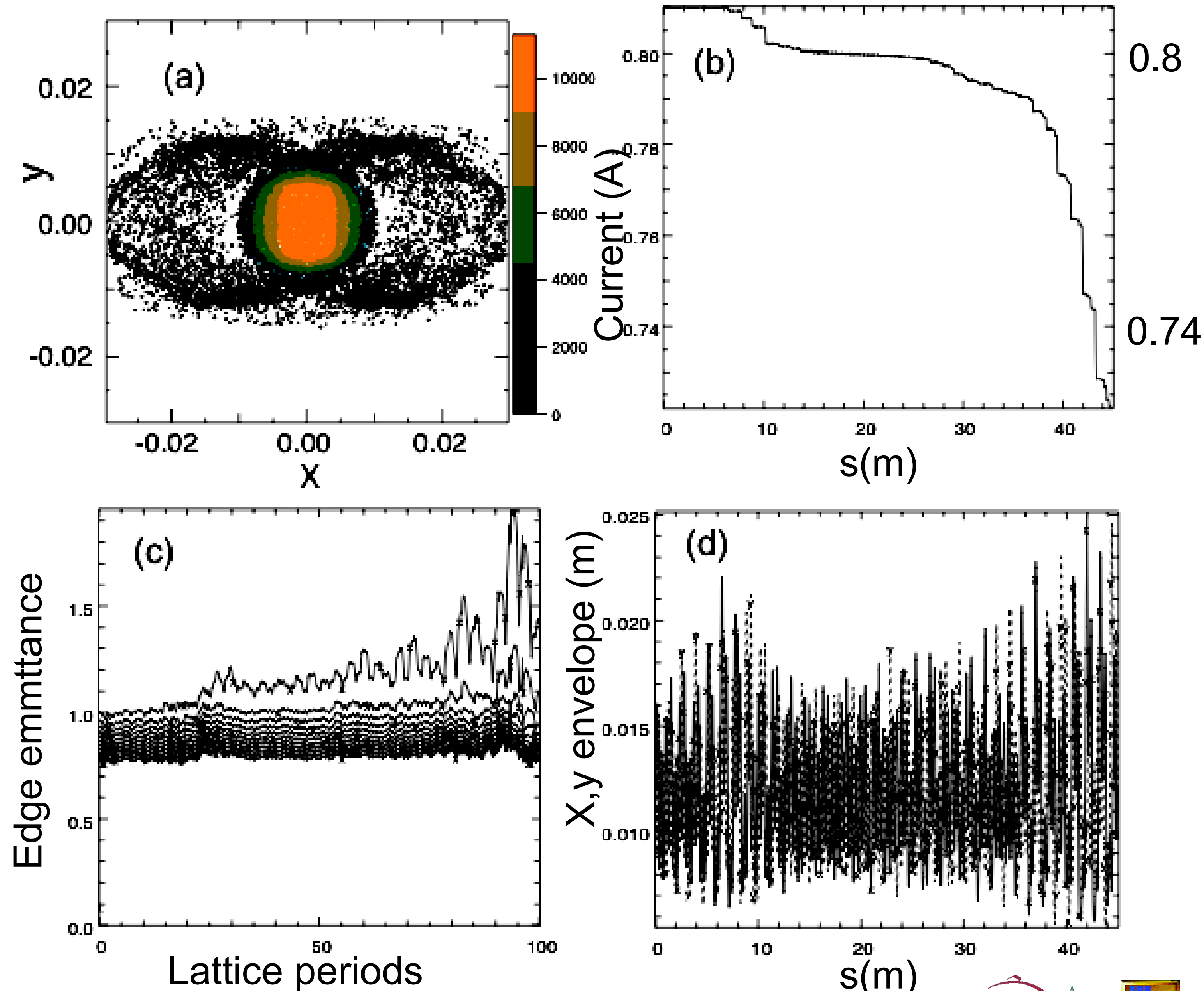


ellipticity

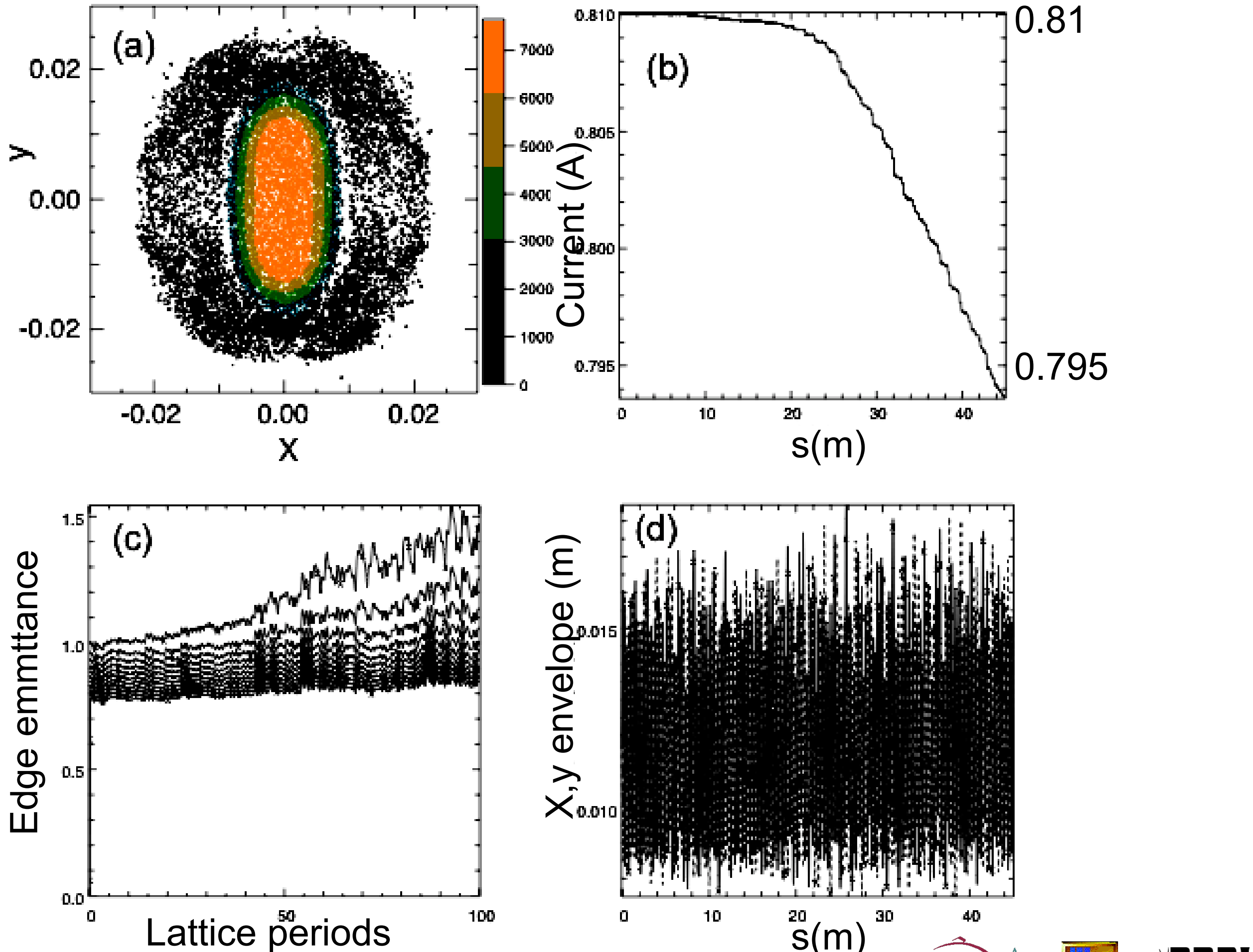
20% constant n_e has little effect



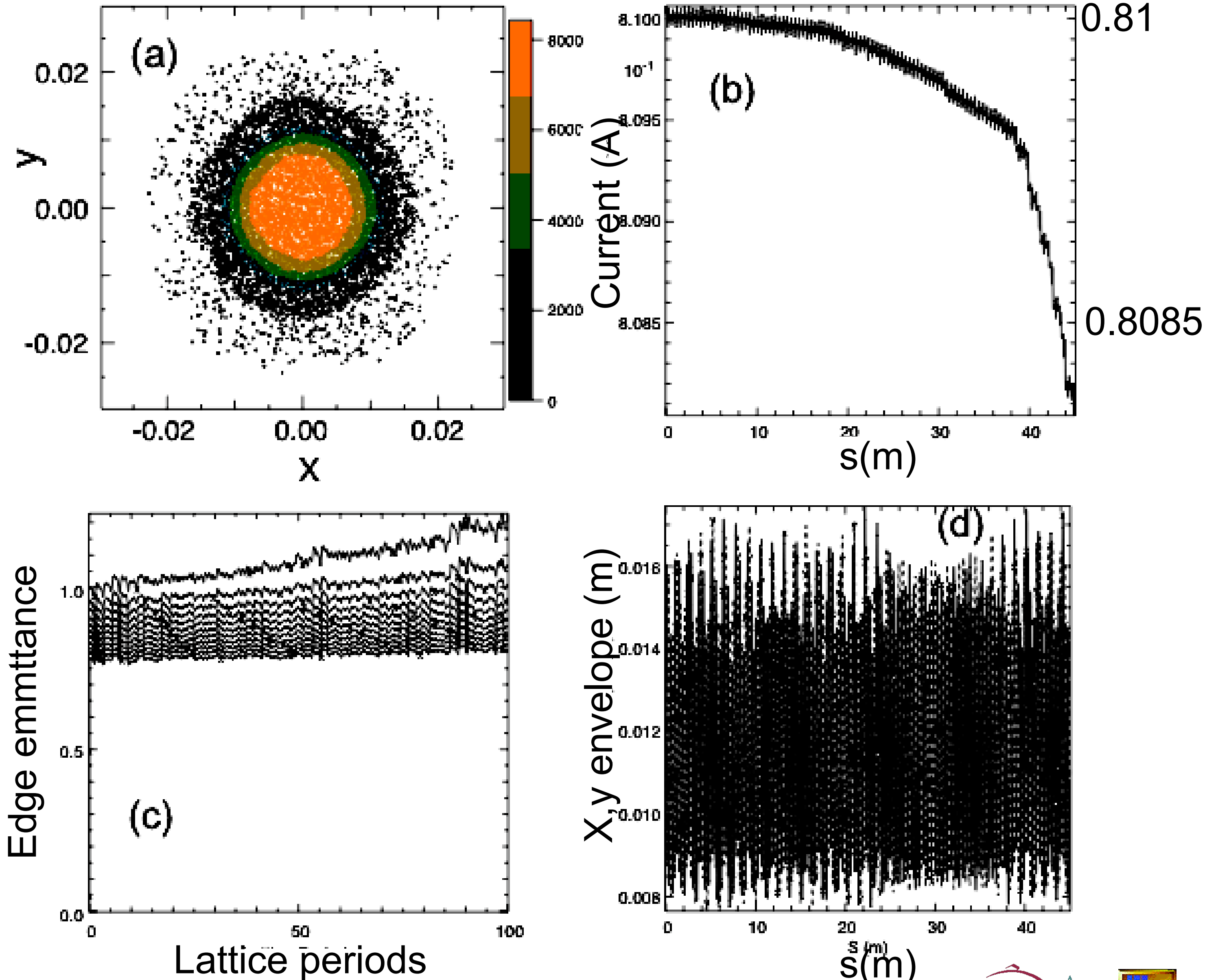
20% mean, 0-40% random n_e produces significant beam loss, envelope growth, halo



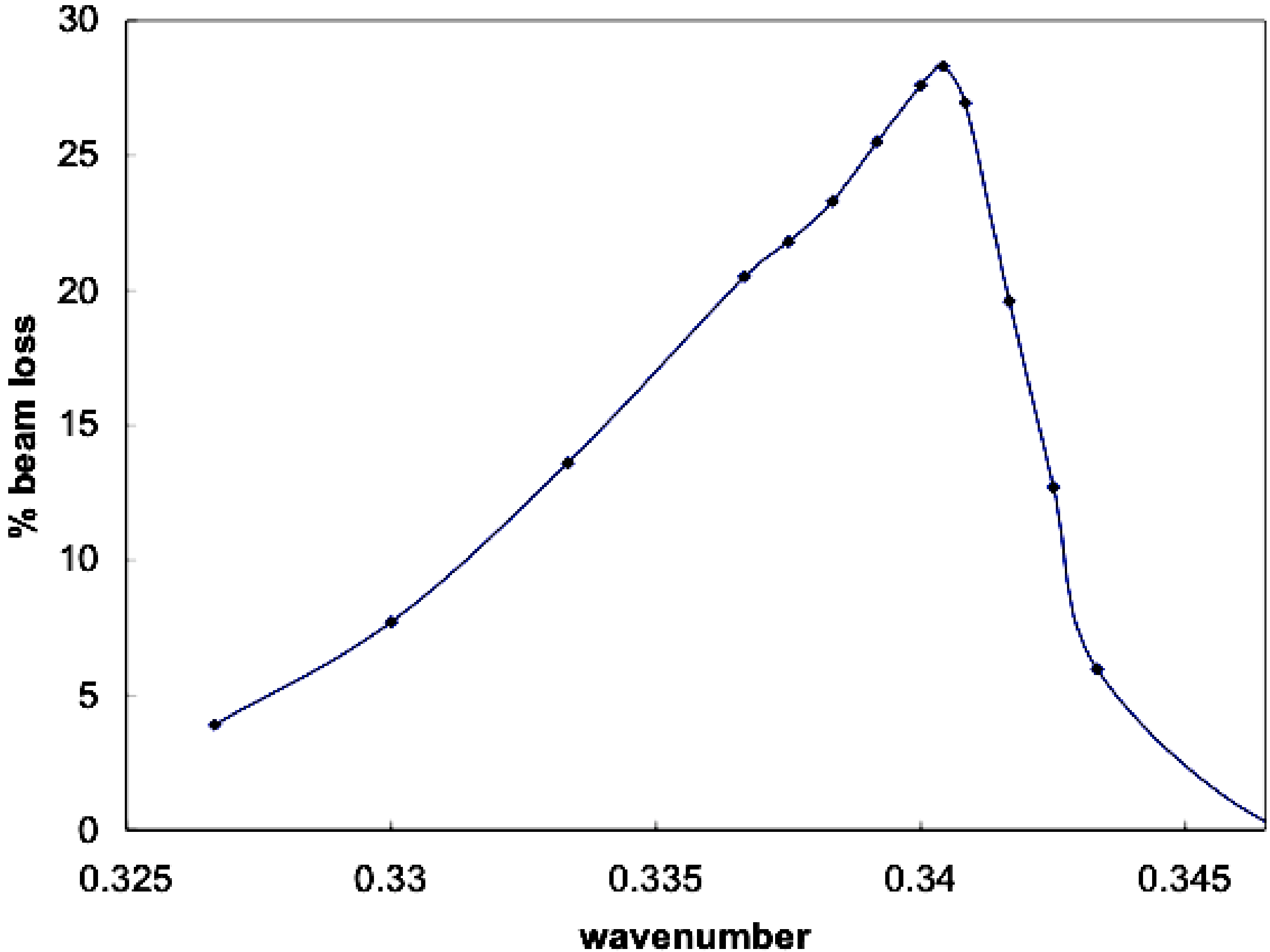
20% n_e with random transverse offsets produces intermediate beam loss, halo, emittance growth



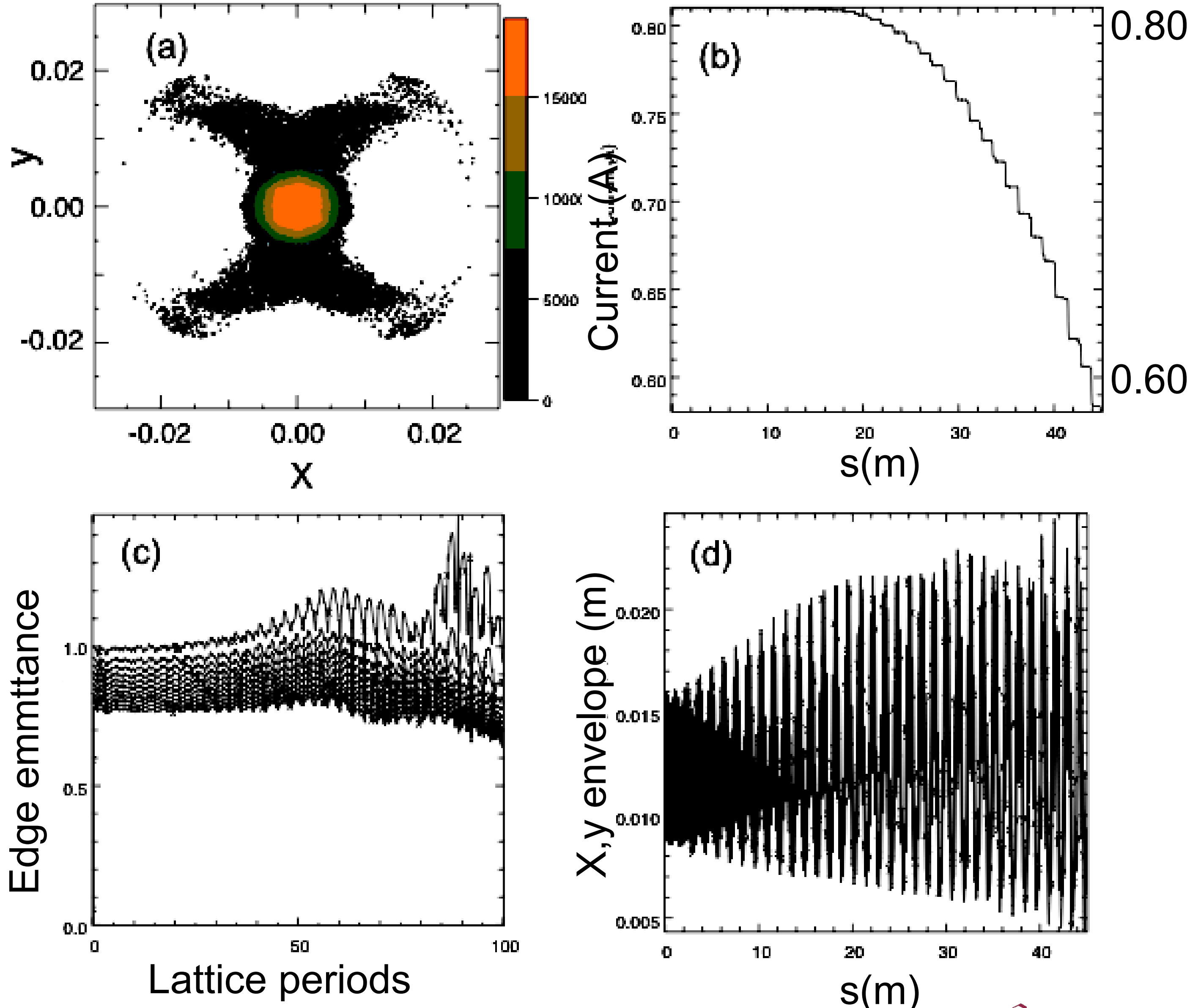
20% n_e with random radial shape variation somewhat worse than const but much better than random amplitude



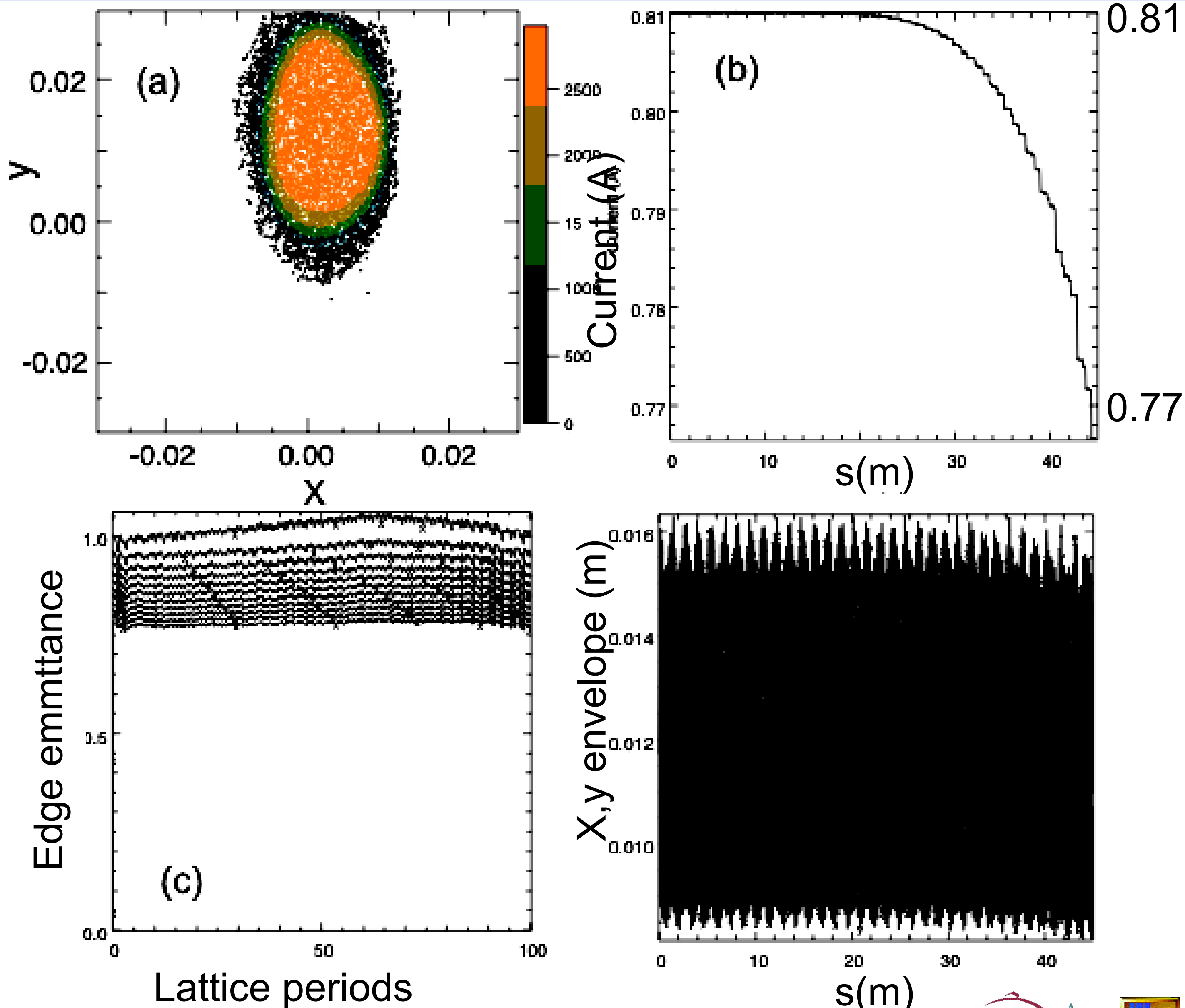
RESONANT perturbations are more damaging: 0-10% sinusoidally varying n_e resonant with breathing mode



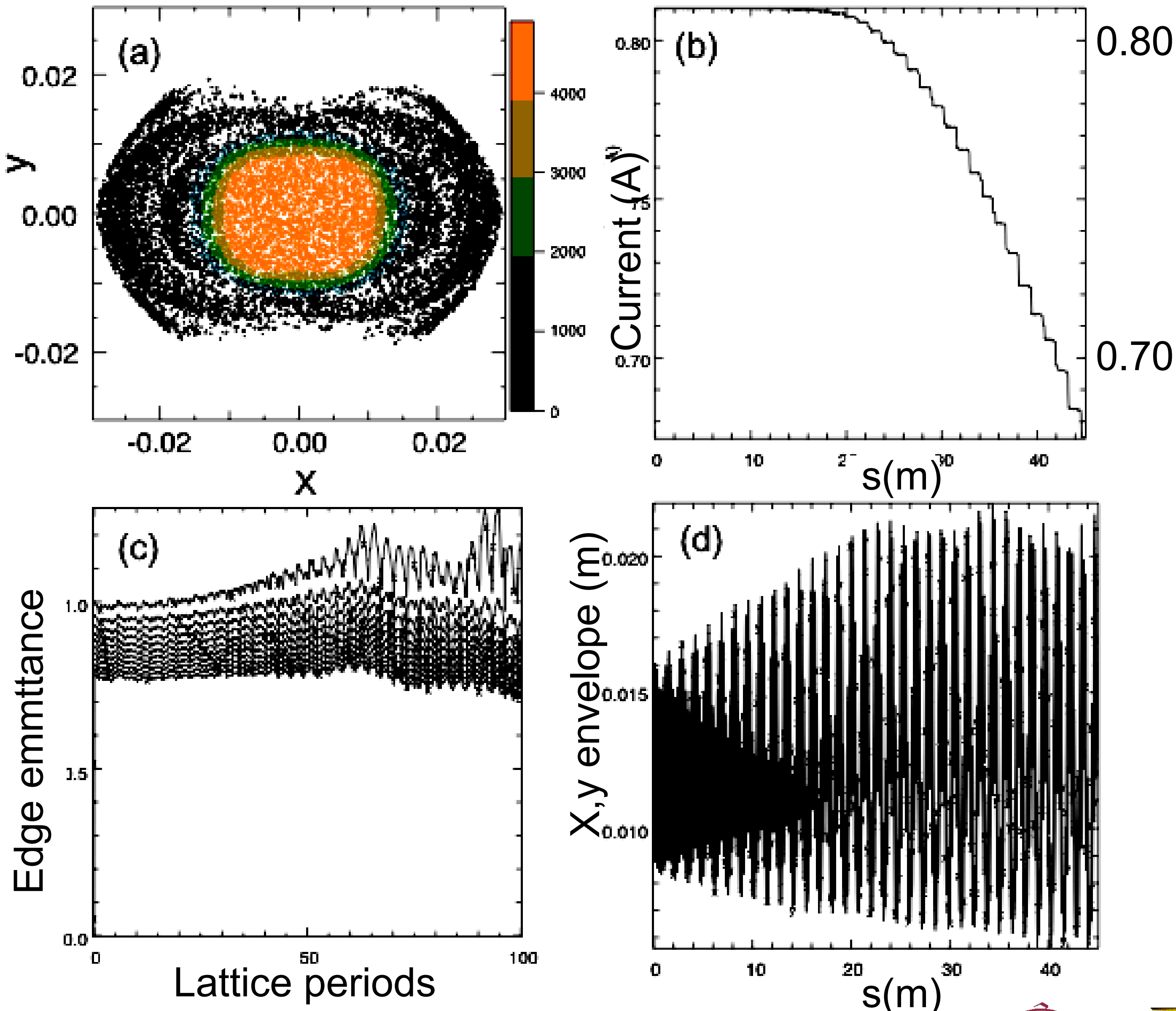
RESONANT perturbations are more damaging: 0-10% sinusoidally varying n_e resonant with breathing mode



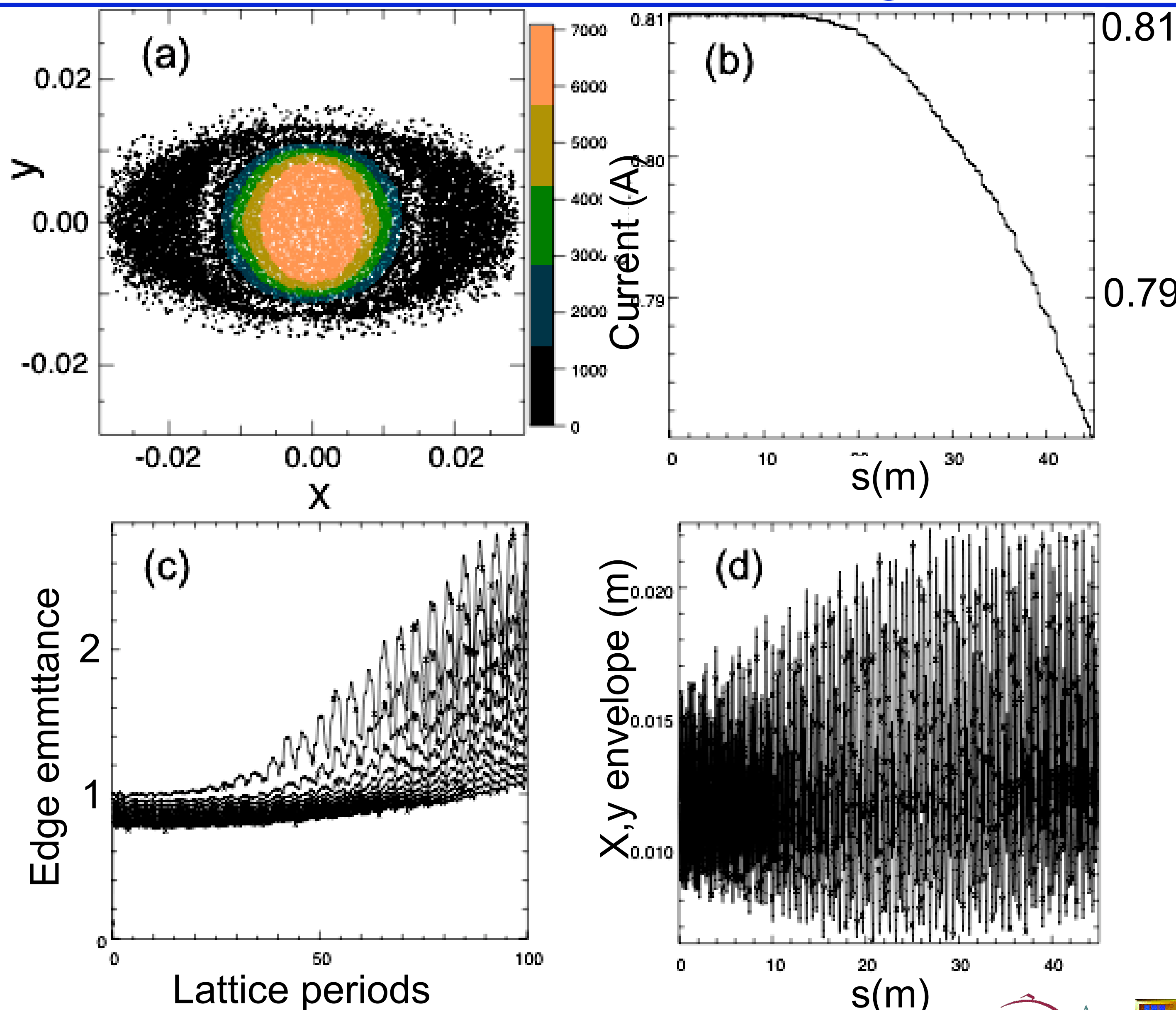
Ecloud offset (10% n_e) displaces ion beam enough for significant scrapeoff but little halo or emittance growth



Sinusoidal radial shape variation (10% n_e, resonant with breathing) less effective than amplitude modulation

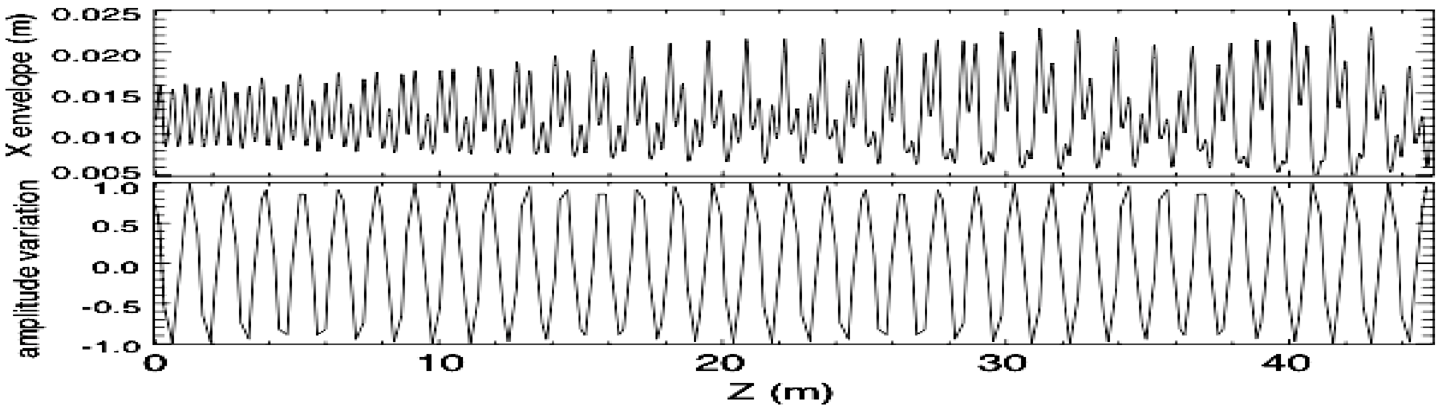


Ellipticity resonant with q-pole oscillation (10% n_e) produces small beam loss but more bulk emittance growth

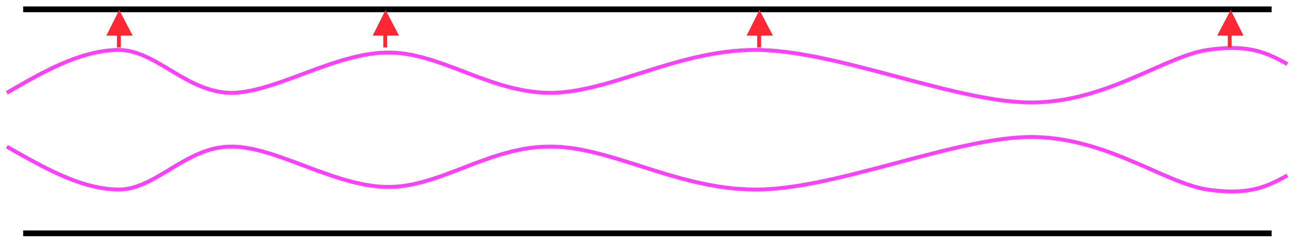


These resonant perturbations are potentially a source of instability

- Ion envelope breathing in phase with e^- oscillations



- Envelope peaks will produce more electrons



- Electrons ~ immobile in beam direction due to quadrupoles
- Perturbation will grow
- Doesn't require const wavenumber (acceleration allowed)

More on instability

- Crude, semi-empirical growth rate (assumptions: coasting beam; wall gas desorption dominates e^- production; neglect neutral time of flight; resonant beam loss $\propto n_e$):

$$\frac{dN_e}{dt} = n_b N_n \langle \sigma v_i \rangle \qquad \frac{dN_n}{dt} = A\Gamma_w \kappa_n$$

with A=area, κ_n = neutrals released per incident ion, N=nV with V=beam volume

- Yields exponential growth with e-folding time:

$$\left[\frac{n_e}{n_b} \frac{Ve}{\langle \sigma v \rangle \kappa_n \Delta I_b} \right]^{1/2}$$

~ 3 μs for simulation parameters (~ τ_b)

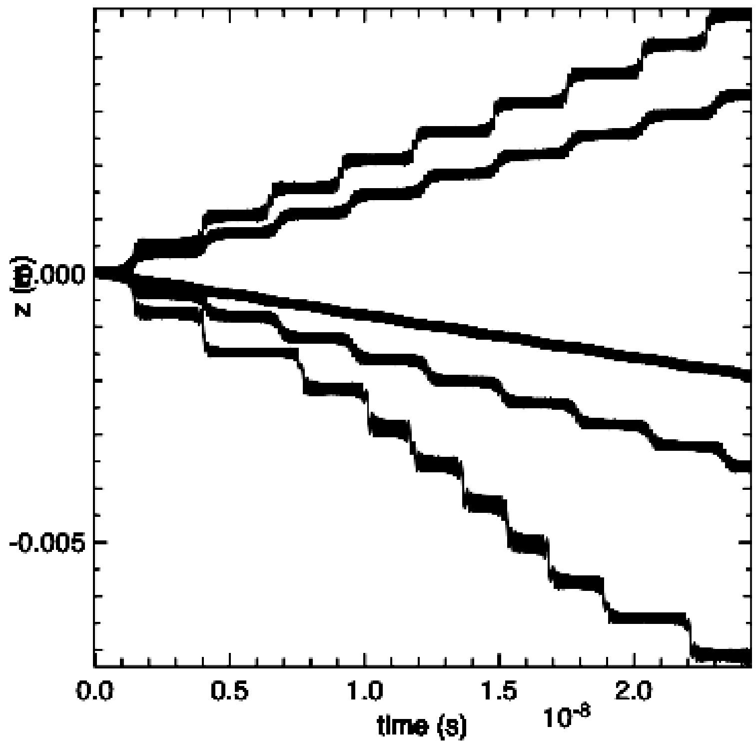
- Growth limited by:
  - Velocity tilt
  - Beam current loss
  - Finite neutral transit time

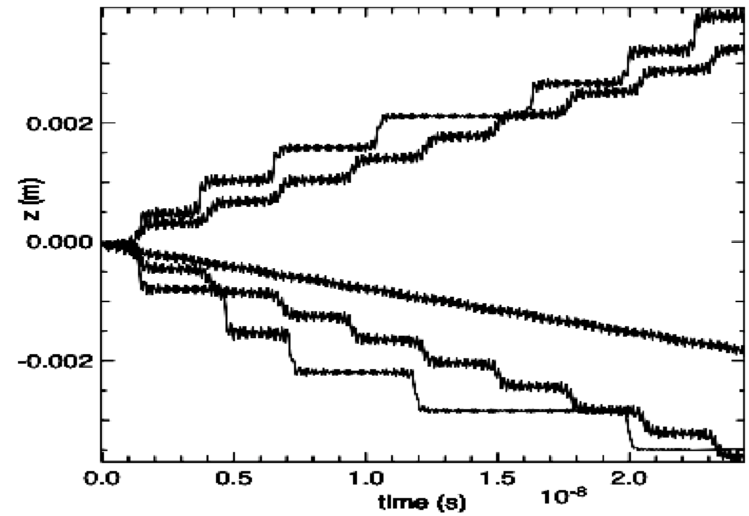
Self-consistent e-i simulation requires technique to bridge timescales

- Need to follow electrons through strongly magnetized and unmagnetized regions ⇒ need to deal with electron cyclotron timescale, ~ 10^{-11} sec.
- Ion timescales > 10^{-8} sec.
- Algorithm to bridge: interpolation between full-electron dynamics (Boris mover) and drift kinetics (motion along B plus drifts).
- Properly chosen interpolation allows stepping electrons on bounce timescale (~10^{-9} sec) yet preserves:
  - Drift velocity
  - Parallel dynamics
  - Physical gyroradius

Interpolated mover: first tests meet expectations

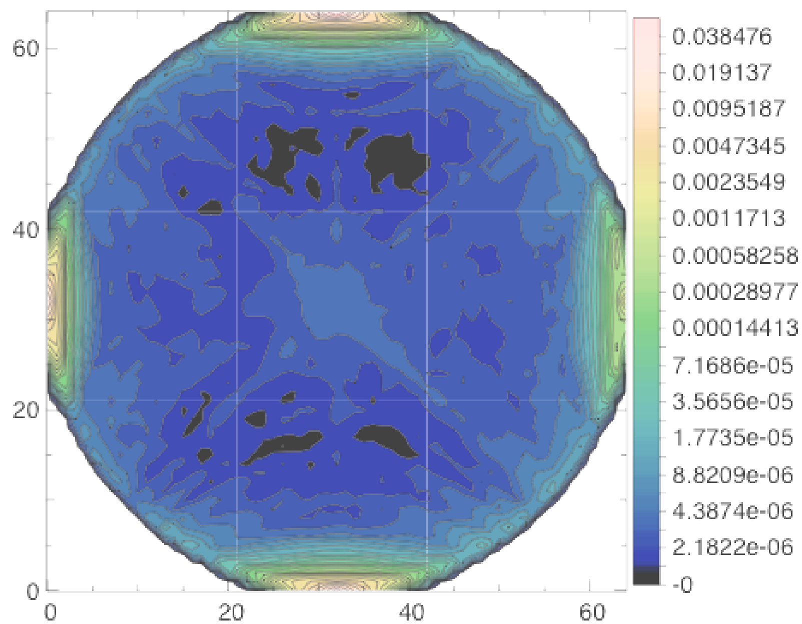
- Compare full orbit to interpolated mover (10x dt).
- Single orbit comparisons of some regular and nonadiabatic (chaotic) orbits:
  - Good agreement on drift & bounce velocity, orbit size for regular orbits
  - Expected non-agreement for chaotic orbits (expect similar statistics; not yet tested).



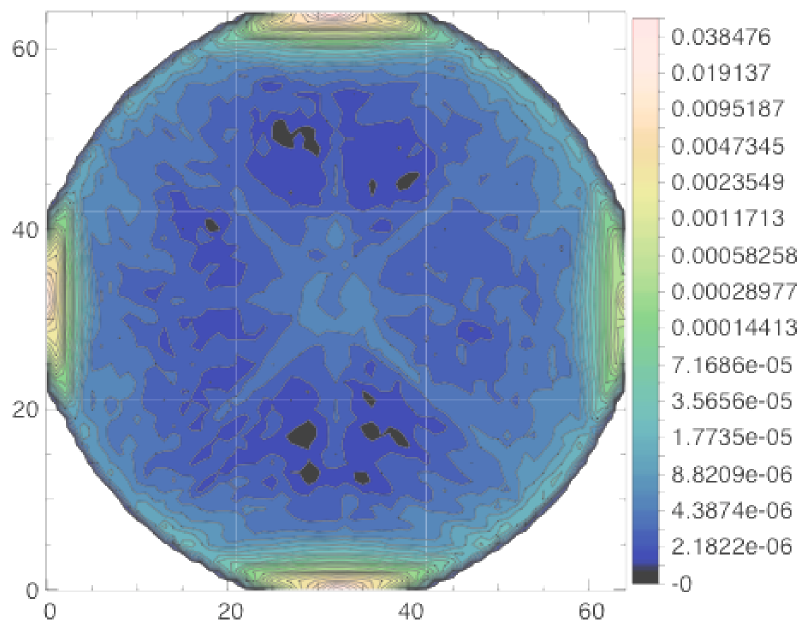


Interpolated model reproduces the e-cloud calculation in < 1/25 time

- Compare full-orbit model, $\Delta t = .25/f_{ce}$, with interpolated model with Δt 25 times longer



Full-orbit



Large-timestep interpolated

Summary/conclusions

- High current, fill factor, pulse length, unclean walls of HIF induction accelerators ⇒ dominant electron source is ionization of neutrals released from walls
  - except ion-impact-produced wall-born electrons for short pulse expts or after drift compression
- Developing self-consistent modeling capability for e-cloud formation, dynamics, effects on ions
- Simulation of dynamics of wall-born electrons from ion impacts shows importance of keeping scattered ions
- Simulation of ion evolution with various model electron distributions shows:
  - effect of random amplitude variations > random offsets > const n_e
  - Resonant sinusoidal perturbations more potent, especially amplitude resonant with breathing mode.
  - Ion beams surprisingly robust: 20% const n_e little effect; several percent resonant perturbation needed for significant impact
  - Possible instability (mild) associated with resonant perturbations