Intro. Lecture 09 Example Simulations*

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US Particle Accelerator School (USPAS) Lectures On
"Self-Consistent Simulations of Beam and Plasma Systems"
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Detailed Outline
Introductory Lectures on Self-Consistent Simulations

Overview of the Warp Code

Example Simulations

- A. ESQ Injector
- B. ....

Contact Information

References

Acknowledgments

Warp Code Overview

See the Warp web site: http://warp.lbl.gov

Example Simulations

Examples to this point have mostly been simply formulated to illustrate concepts. Here, we present results from more complex simulations carried out in support of experiments, theory, and for machine design. Simulations highlighted include:

- Electrostatic Quadrupole Injector
- Multi-beamlet Injector
- Collective Mode Effects
- Detailed Transport Lattice Design
- Transport Limits in Periodic Quadrupole Focusing Channels
- Electron Cloud Effects for Ion Beam Transport

All these simulations, as well as many of the preceding illustrations in the lecture notes, were produced with the Warp code described in S9. Only select issues from the problems are highlighted.

Example: Electrostatic Quadrupole Injector

See handwritten notes from USPAS 06 for remaining slides

- Will be updated in future versions of the notes

89

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WARP Code Overview

Electrostatic Multi-dimensional PIC Code

WARP3d – x, y, z, p_x, p_y, p_z
Moves in t

Many Fieldsolvers:
SOR, Multigrid, FFT,
FFT + Tridiag, FFT + Cap Ma

WARPxy – x, y, p_x, p_y, p_z
Moves in s

WARPrz – r, z, p_r, p_z, p_θ
Moves in t

WARPenv – envelope solver
Used to seed / load PIC
r_x, r_y, r_x', r_y'
Advances in s

Hermes – Fluid $\parallel$ + Gridded
Space Charge Field

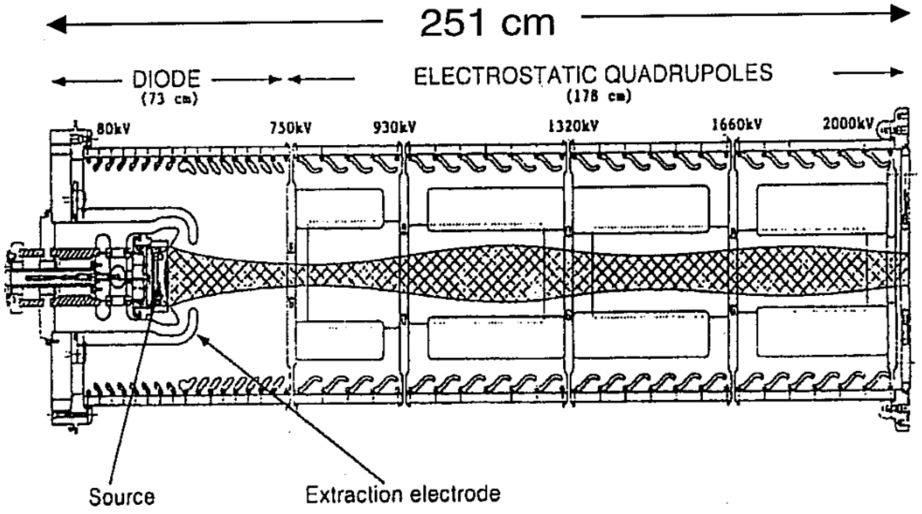
- Common diagnostic tools built around gist. graphics

- Run with python Interpreter

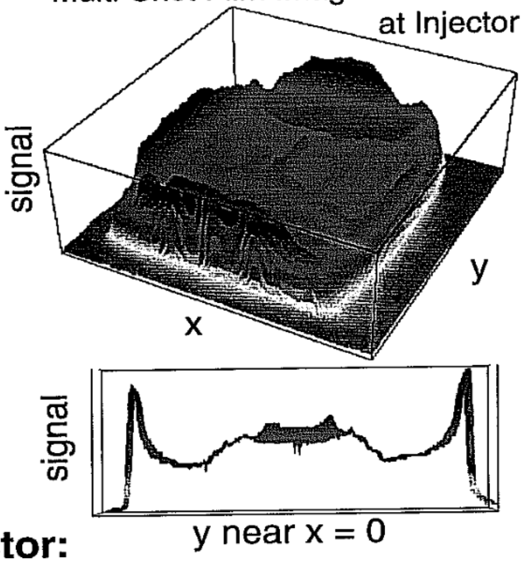
Example Script
"ag-slice.py"

3D PIC simulations are being used to guide retrofits of an existing ESQ injector at LBL

1st principles, mid-pulse 3D simulations have been carried out to guide injector retrofits aimed at decreasing beam aberrations



Multi-Shot Film Images of Beam at Injector Exit



Parameters expected at exit of retrofitted injector:

Energy:	**E = 1.71 MeV**	
Current:	**I = 692 mA, K**	
Emittance:	**ε_n = 1.1 π mm-mrad**	**rms edge measure**
	~ 0.7 π mm-mrad	**measure eliminating empty entrained space**
Envelope:	**r_x = 56.3 mm**	**r_x' = 53.8 mrad**
	r_y = 55.7 mm	**r_y' = -44.8 mrad**

S10 Example PIC Simulations

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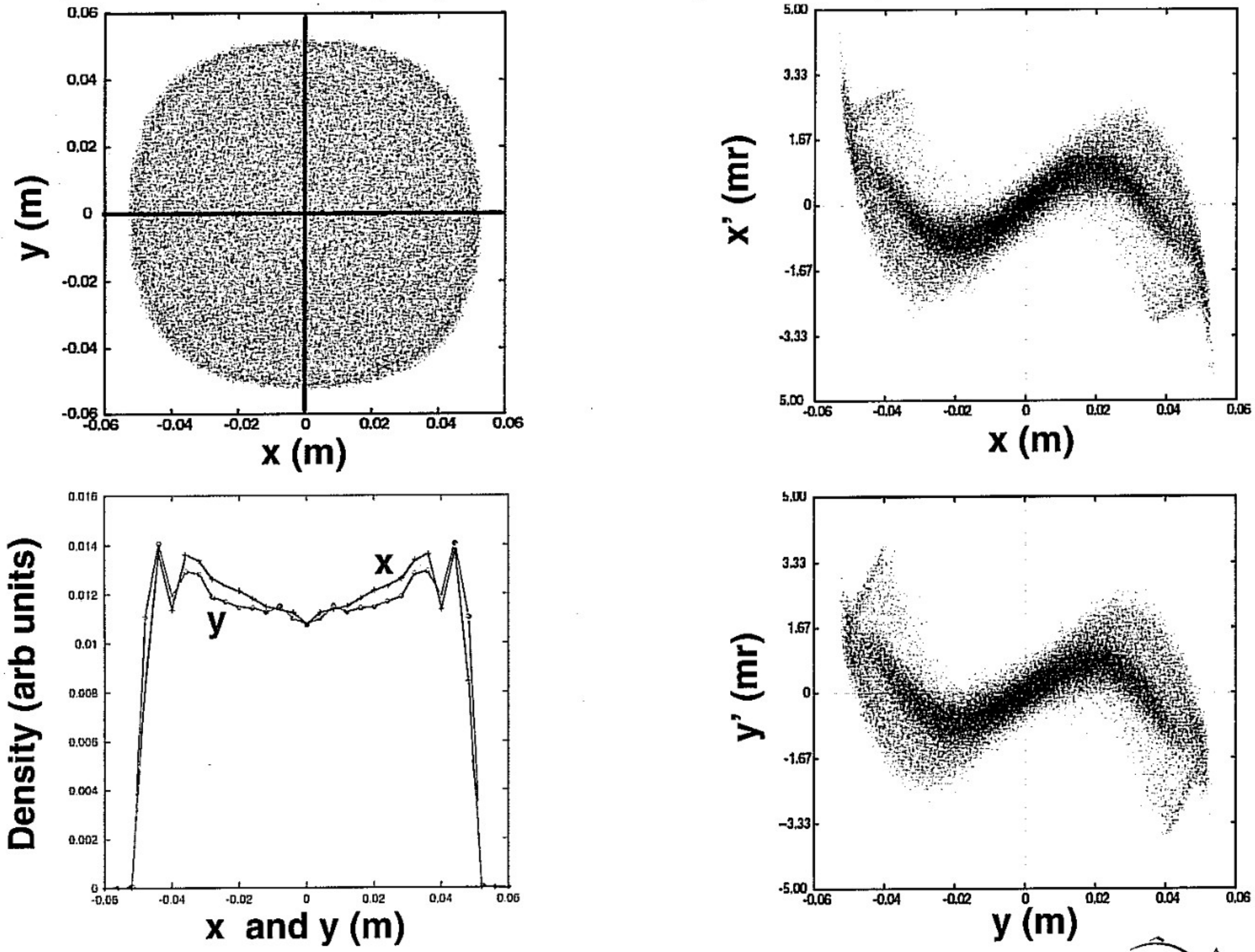
HCX Injector: Simulations show distribution distortions in the retrofitted injector should be more modest

Mid-pulse distribution projections at exit plane of injector



Overall convergence and divergence angles removed to illustrate distortions

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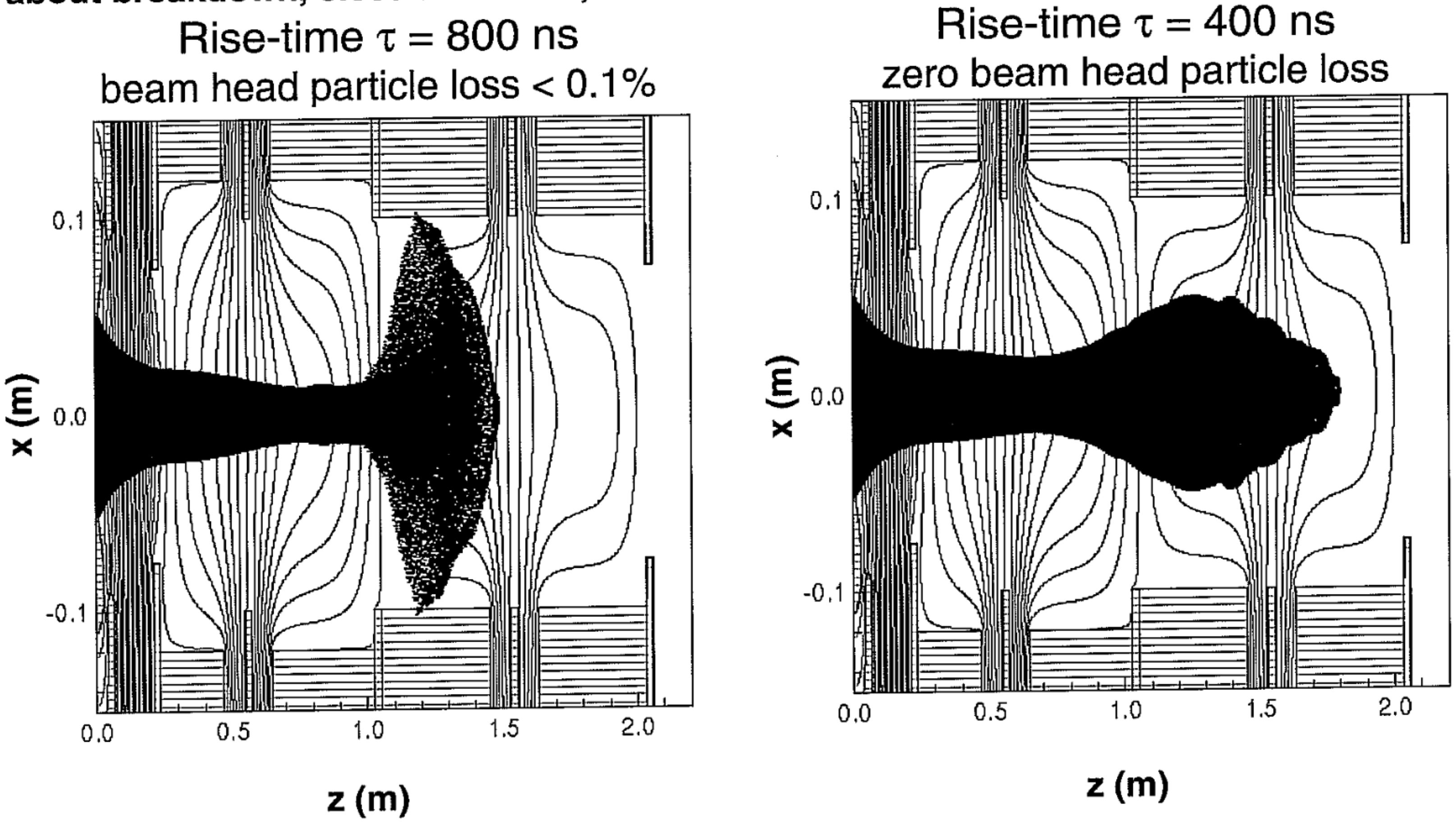
Simulations show how waveform rise-time determines beam head mismatch

Tuned 1d diode voltage waveform rise-time is 400 ns -- deviations from this lead to significant mismatch effects in the beam head and particle loss with resultant worries about breakdown, electron effects, etc.



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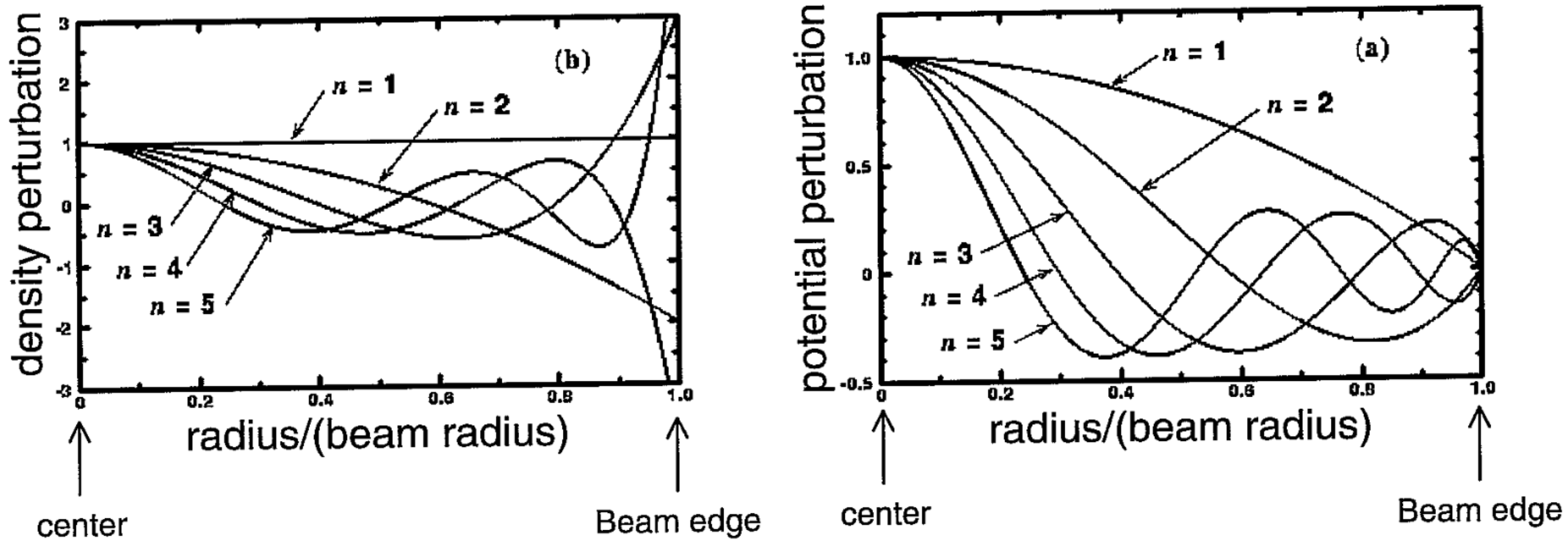
Initial distribution distortions will launch a spectrum of collective mode perturbations that evolve

Kinetic and fluid theories have been employed to analyze perturbations on a uniform density intense-beam equilibrium [Lund and Davidson, Phys. Plasmas, 5 3028 (1998)]

Small Amplitude Perturbations (arbitrary units, kinetic and fluid theory)



Mode Dispersion Relation (fast branch, from fluid theory)

$$\frac{\sigma_n}{\sigma_0} = \sqrt{2+2\left(\sigma/\sigma_0\right)^2(2n^2-1)}$$

σ_n= mode phase advance

n = 1,2,3, ……

Example:

$\sigma_0 = 80^\circ$, $\sigma/\sigma_0 = 0.2$

$\sigma_1 = 115^\circ$, $\sigma_5 = 182^\circ$, ….

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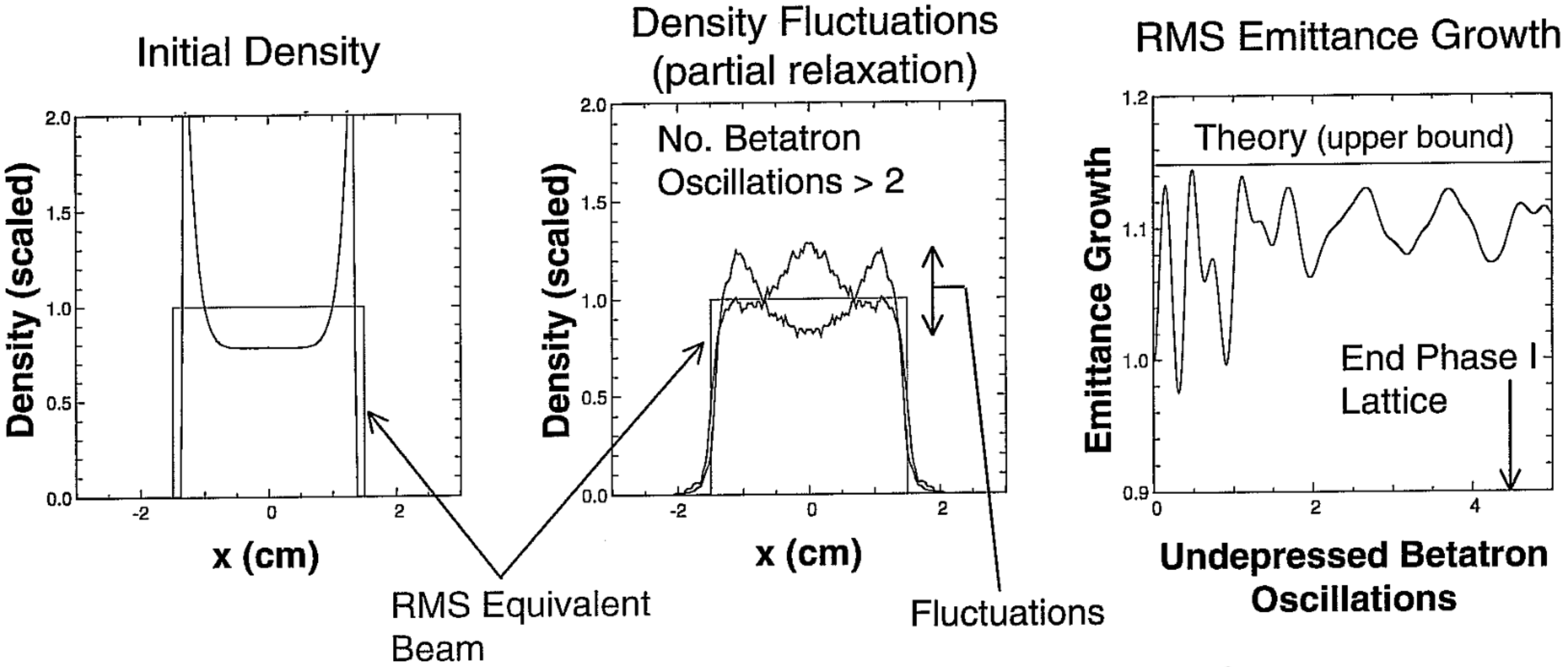
Perturbations launched by initial distribution nonuniformities can phase-mix to a more uniform profile with increased emittance

Mode spectrum launched can undergo a rapid cascade, settling to a smaller amplitude and lower order distortion

- ❒ Approximate conservation constraints employed to bound emittance increases resulting from full relaxation to a uniform profile [Lund, Lee, and Barnard, Proc. Linac 2000, pg. 290]
- ❒ How will such evolutions influence the range and interpretation of measurements



Initial Density

Density Fluctuations (partial relaxation)

RMS Emittance Growth

RMS Equivalent Beam

Fluctuations

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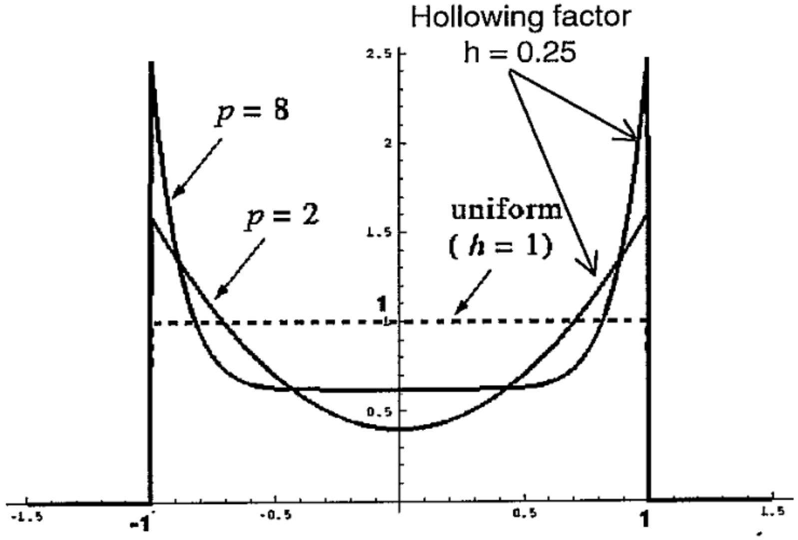
Analytic theory has been used to parametrically bound emittance growth due to the relaxation of space-charge nonunifomities

Approximate conservation constraints can be employed to estimate maximal emittance increases resulting from the relaxation of an initial nonuniform density profile to a final, uniform profile [Lund, Lee, and Barnard, Proceedings Linac 2000, Monterey, CA, pg. 290]

Initial Density

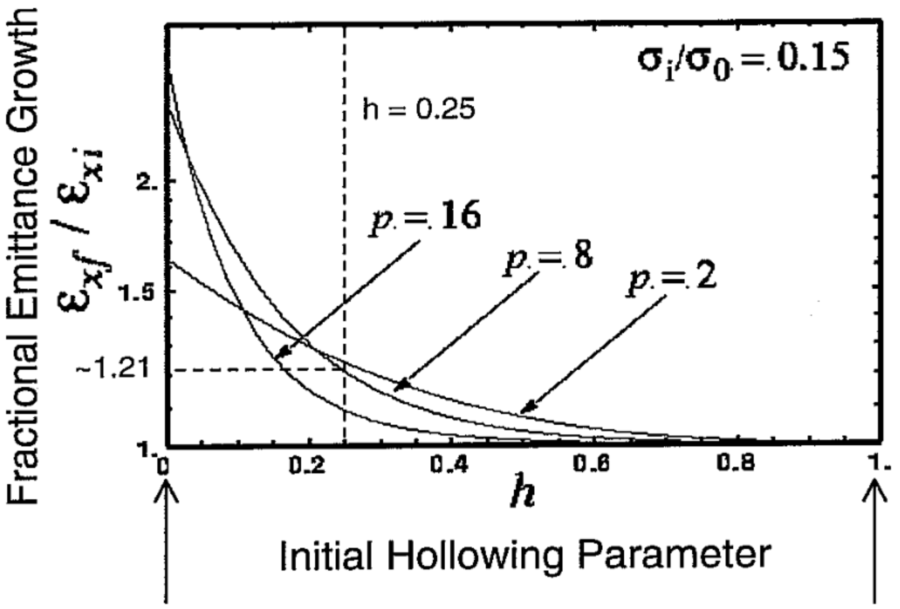


Normalized Radial Coordinate

hollowing ~ r^p

h = ratio min to max density

Emittance Growth on Relaxation



Extremely Hollowed

Uniform

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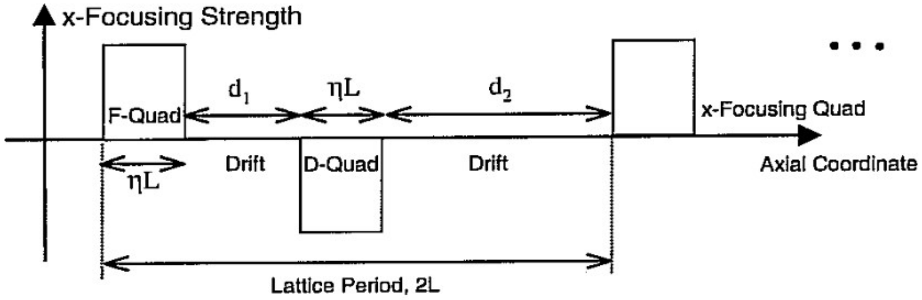
HCX Phase II: A wide range of parametric simulations have been carried out with realistic magnetic transport lattices

A syncopated magnetic transport lattice of ~ 50 lattice periods has been designed



HCX:

η = Quadrupole Occupancy $(0 < \eta < 1)$ $\eta = 0.453$

α = Syncopation Factor $(0 < \alpha < 1)$ $\alpha = 0.248$

Drifts:

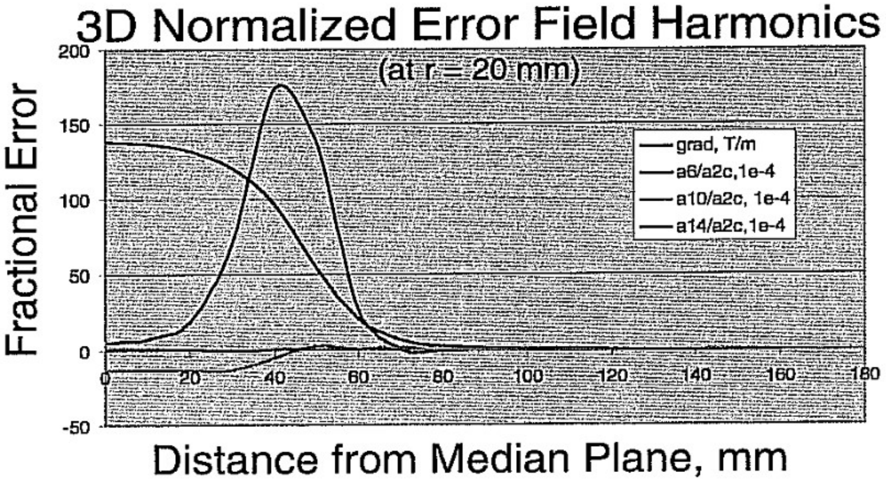
$d_1 = \alpha(1-\eta)\eta L$

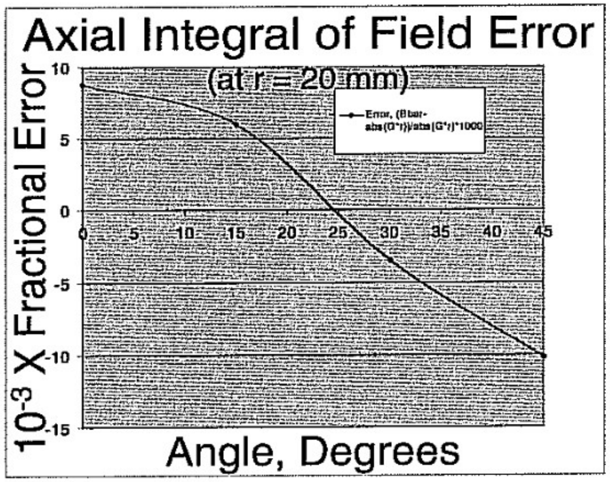
$d_2 = (1-\alpha)(1-\eta)\eta L$

Superconducting magnetic quadrupoles have been designed and prototyped

$r_p = 29.5$ mm $B_q' = 104$ T/m (max) $B_q \sim 6$ Tesla (wire)

$\ell = 136$ mm $\ell_{\mathrm{eff}} = 101$ mm Integrated Field Error $< 15 \times 10^{-3}$





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109

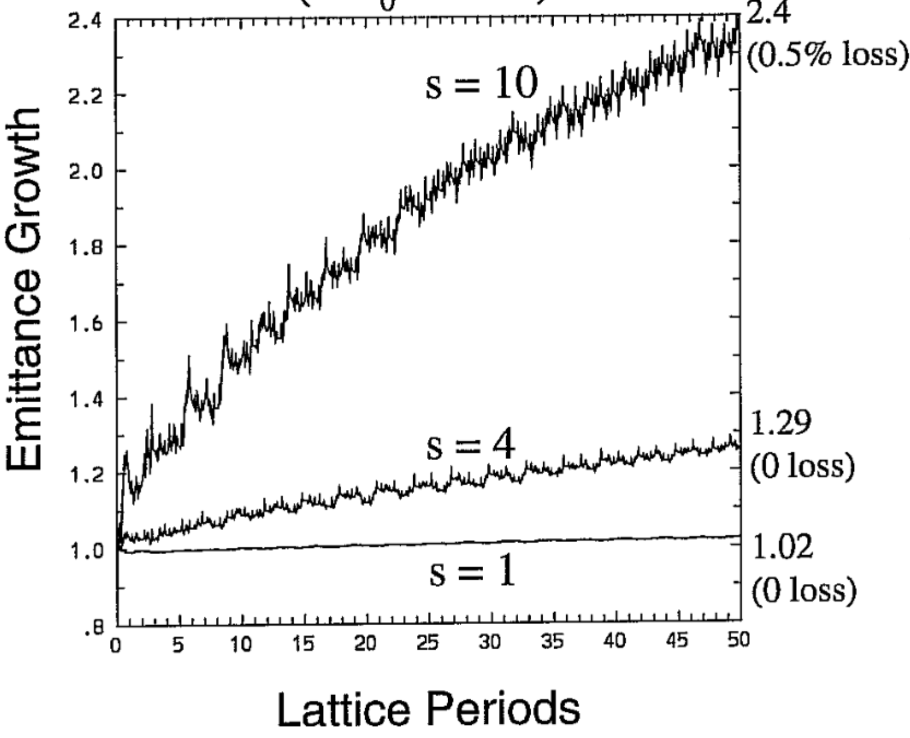
HCX Phase II: Processes influencing beam quality and control have been explored --- Example: Nonlinear applied fields and beam quality

Full 3D magnetic field is resolved as:

$$\vec{B} = \vec{B}_{quad} + \delta\vec{B} \qquad \delta\vec{B} \rightarrow s \cdot \delta\vec{B}$$

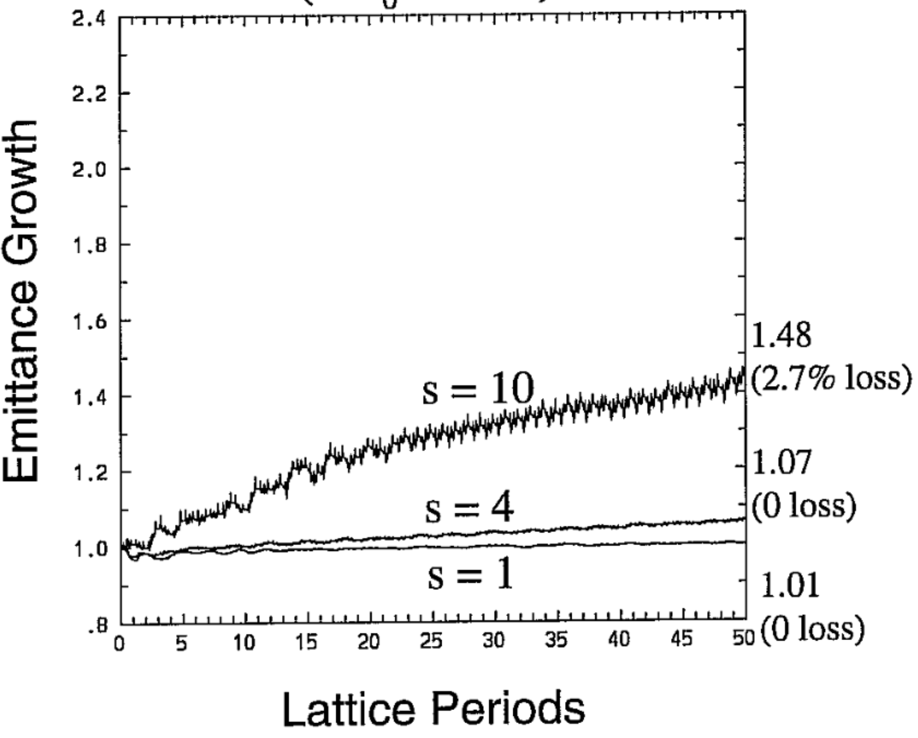
Very Strong Space Charge

$(\sigma/\sigma_0 = 0.086)$



Intermediate Space Charge

$(\sigma/\sigma_0 = 0.248)$



S.M. Lund 6/1

Initial KV Distribution

See also Reiser Text, pg 495.

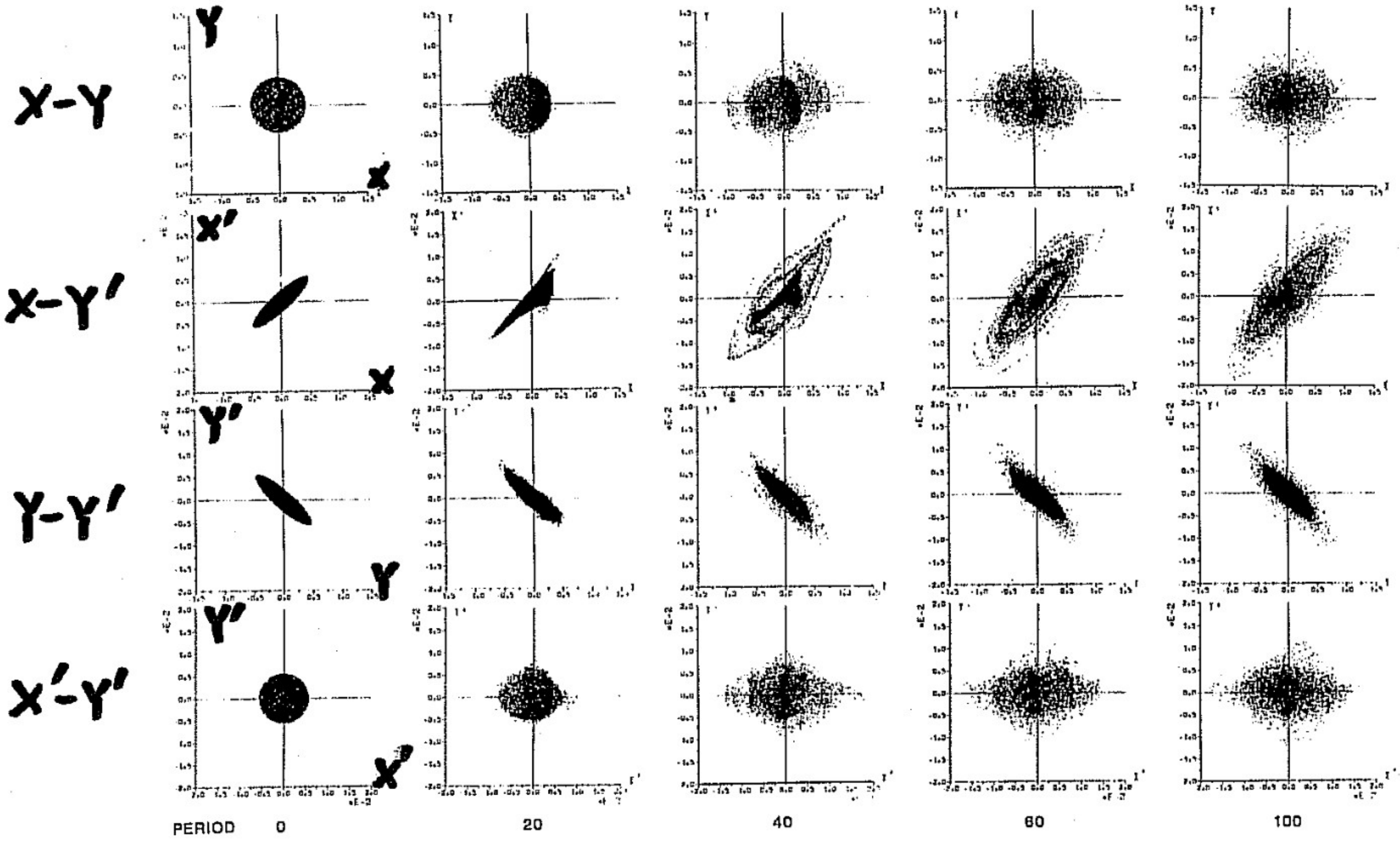


FIGURE 2 Transformation of an initial K-V distribution through the GSI FODO channel at $\sigma_0 = 90°$, $\sigma = 41°$.

J. Struckmeir, J. Klabunde, and M. Reiser, Part. Accel. 15, 47 (1984).

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Initial Gaussian Distribution

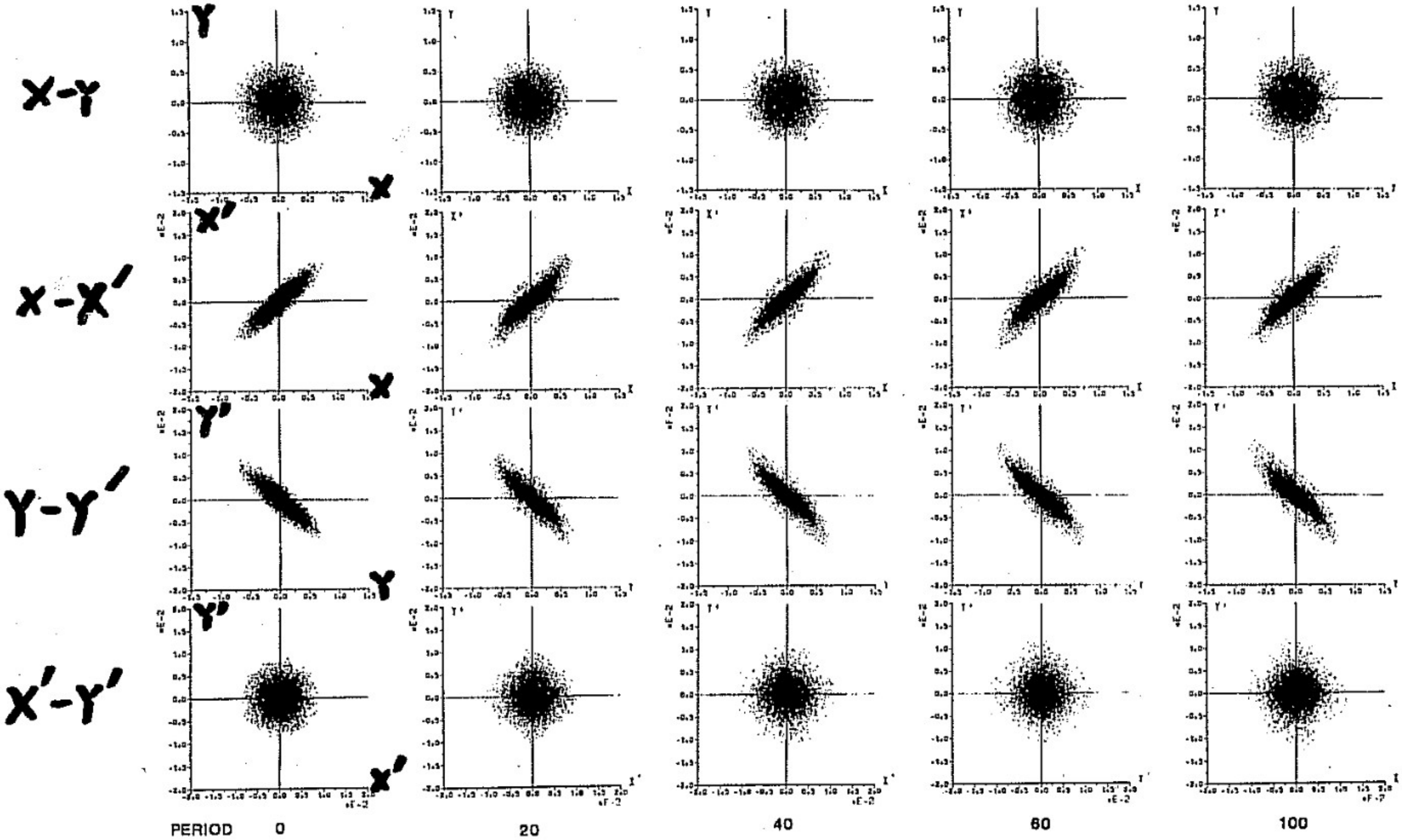

FIGURE 6 Transformation of an initial Gaussian distribution (rms-matched) through the GSI FODO channel at $\sigma_0 = 90°$, $\sigma = 41°$.

J. Struckmeir, J. Kabunde, and M. Reiser, Part. Accel. 15; 47 (1984)

S.M. Lund 64/

GROWTH OF DIFFERENT DISTRIBUTIONS 61

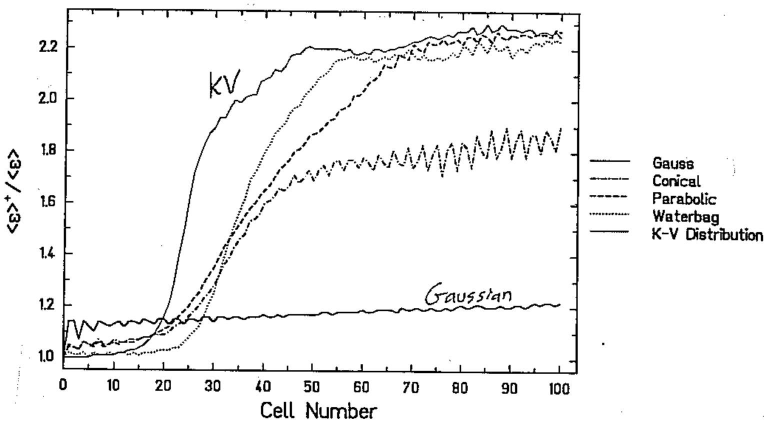

FIGURE 7 Emittance growth factors versus the number of cells obtained from particle simulations for initial K-V, waterbag, parabolic, conical and Gaussian distributions at $\sigma_0 = 90°$, $\sigma = 41°$.

From J. Struckmeer, J. Kabunde, and M. Reiser, Part. Accel. 15 47 (1984).

Corrections and suggestions for improvements welcome!

These notes will be corrected and expanded for reference and for use in future editions of US Particle Accelerator School (USPAS) and Michigan State University (MSU) courses. Contact:

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Please provide corrections with respect to the present archived version at:

https://people.nscl.msu.edu/~lund/uspas/scs_2016

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References: For more information see:

These US Particle Accelerator School (USPAS) course notes are posted with updates, corrections, and supplemental material at:

https://people.nscl.msu.edu/~lund/bpisc_2014

This course evolved from material originally presented in a related USPAS course :

JJ Barnard and SM Lund, *Beam Physics with Intense Space-Charge,* USPAS:
http://people.nscl.msu.edu/~lund/bpisc_2011 2015 Lecture Notes + Info

Also taught at the USPAS in 2011, 2008, 2006, 2004, and 2001
and a similar version at UC Berkeley in 2009

This course serves as a reference for physics discussed in this course from a numerical modeling perspective.

References: Continued (2):

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Review of Initial Distribution Loads

S. Lund, T. Kikuchi, and R. Davidson, "Generation of initial kinetic distributions for simulation of long-pulse charged particle beams with high space-charge intensity," PRSTAB **12**, 114801 (2009)

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