Intro. Lecture 05: Diagnostics*

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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

Diagnostics

A. Overview

B. Snapshot Diagnostics

- Phase-Space Projections
- Fields
- Moments
- Movies

C. History Diagnostics

Diagnostics A: Overview

Diagnostics are *extremely* important. Without effective diagnostics even a correct and well converged simulation is useless. Diagnostics must be well formulated to display relevant quantities in a manner that increases physical understanding by highlighting important processes. This can be difficult since there can be a variety of issues and multiple effects taking place simultaneously.

Diagnostics can be grouped into two broad categories:

1) Snapshot Diagnostics
(Fixed instant in time)
- Examples: Plots of particle distribution projections at a particular values of s or t
- Data can be saved to generate plots after the run or just the needed plots can be generated during the run using linked graphics packages etc.
- Sometimes presented as a sequence of images (movie) to show evolution

2) History Diagnostics
(Time history of evolution)
- Examples: plots of moment for the statistical beam centroid, envelope, and emittances
- Data for history plots must be accumulated and saved over several simulation advance steps

What diagnostics are most beneficial depend on what one is modeling

- Can be highly specific to the problem
- Use quantities people are familiar with to most effectively communicate
- May need different targeted diagnostics for physics applications and detailed verification/benchmarking of simulations/algorithms

Diagnostics plots can be generated in a variety of ways

- Routines within the code
  - Best to be flexible: easily reconfigured to context needed
  - Python diagnostic scripts in Warp provide considerable flexability
- Dumping organized data for post processing
  - Organization important: storage requirements can be large

Can be effective to numerically synthesize laboratory equivalent diagnostics to ease left right comparisons with experiment

- Experiments very difficult and making context as similar as possible can alleviate confusion
- Simulations can simultaneously measure many quantities: if limited context synthetic diagnostics agree with experiment, it can increase confidence in broader implications of the simulation data which may not be easily measured

Old Saying: A picture is worth a thousand words

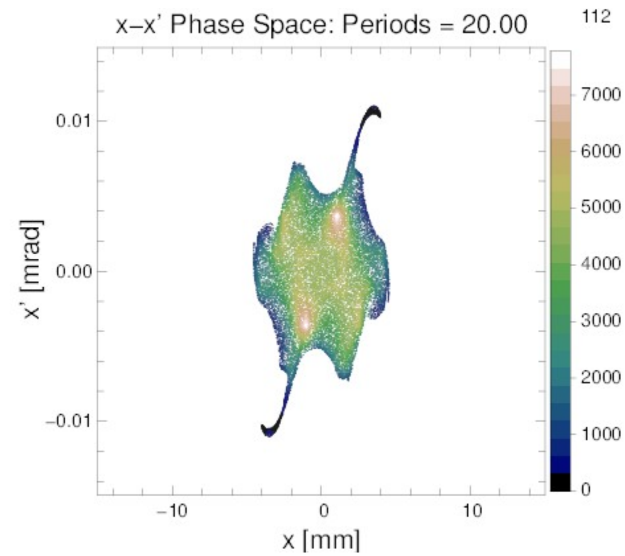
Present Context?: A good diagnostic plot is worth TBs of data

B. Snapshot Diagnostics: Particle Phase-Space Projections

Snapshot diagnostics take an image of the beam at a particular instance in time or axial coordinate as the beam advances. Includes:

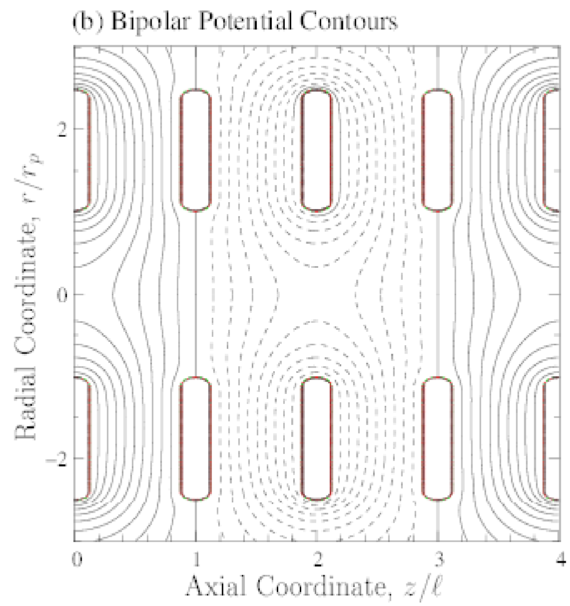
- Particle Phase Space Projections
  – Examples: x-y, x-x', y-y', x'-y', ….

x-x' phase space projection of unstable beam



- Fields
  – Example: Contours of Self-Field Potential ϕ

r-z ES potentials of a periodic einzel lens structure



- Moments

  Commonly gathered over a moving window over the beam pulse

  – Example: Pulse current, transverse rms beam extent and rms emittance as a function of z over beam pulse

Beam current: $$I(z) = \int d^2x \; J_z(\mathbf{x}, t = \text{const})$$

Perp rms extent: $$r_x(z) = 2\langle x^2 \rangle_\perp^{1/2}$$

Perp rms emittance: $$\varepsilon_x(z) = 4\left[\langle x^2 \rangle_\perp \langle x'^2 \rangle_\perp - \langle x x' \rangle_\perp^2\right]^{1/2}$$

Add mountain range plot in future version

- Movies

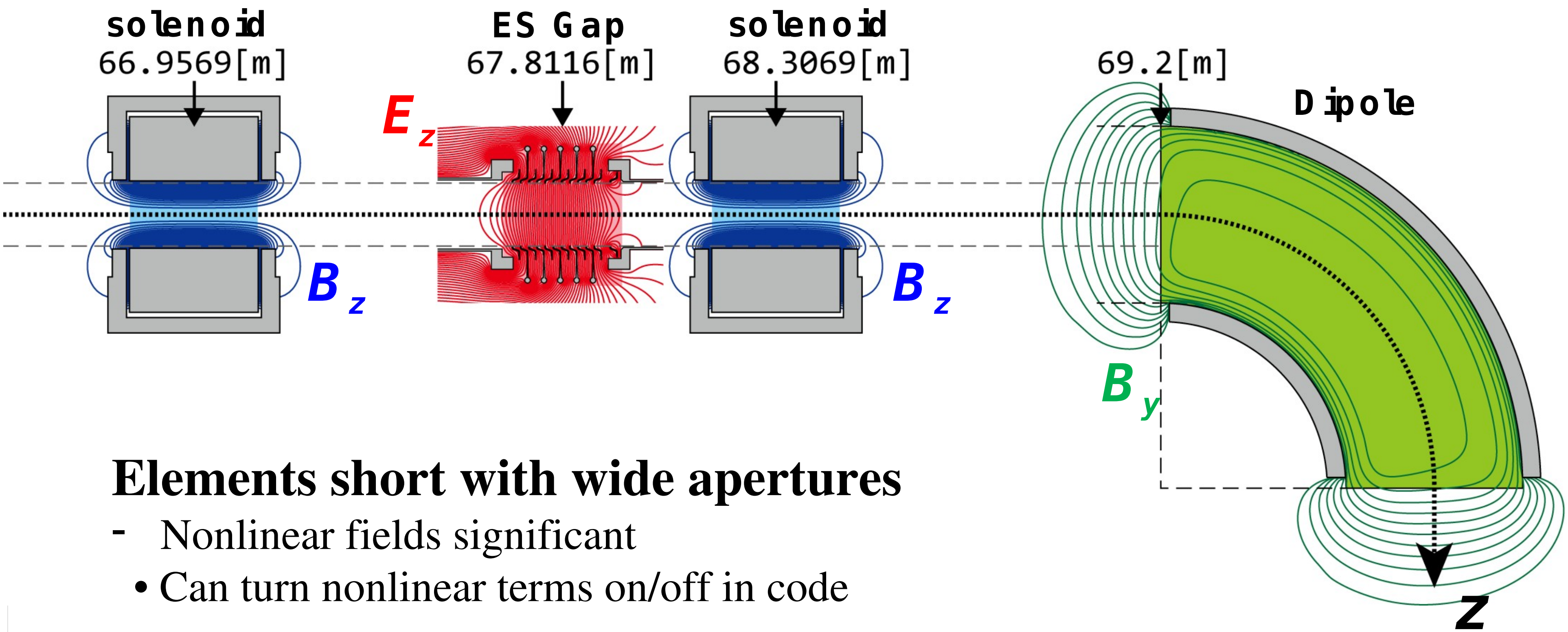
  Help illustrate trends and great for getting attention to topics. Correlated evolution of multiple quantities most useful but difficult to make. Will be posting Warp guidelines/tools soon.

  – Example: play in class: space-charge wave evolution + multispecies beam evolution

FRIB movie from K. Fukushima (KEK/MSU)

Lattice elements modeled at high levels of detail for importing into simulations

K. Fukushima (KEK/MSU)



Elements short with wide apertures

- Nonlinear fields significant
  - Can turn nonlinear terms on/off in code

- Fringe fields neighboring elements can overlap
  - Modeled in code: find implications

History Diagnostics: Moment Evolutions

Time histories of quantities are highly useful. Common measures include

- Pulse energy, current
- Moments: center of mass phase-space, rms extents, emittances, etc

Histories of invariants can be particularly useful for checks of simulations

Moments:

Typically have a lesser degree of noise since they generally average over many macroparticles

- 2D case => full beam
- 3D case => local *z*-slice of beam
- Examples:

Beam Current: $\mathrm{I} = \int d^2x \; J_z(\mathbf{x}, t)$

Beam Centroid Phase-Space:

$$X = \langle x \rangle_\perp \qquad X' = \langle x' \rangle_\perp$$
$$Y = \langle y \rangle_\perp \qquad Y' = \langle y' \rangle_\perp$$

Beam Emittance:

$$\varepsilon_x = 4\left[\langle x^2 \rangle_\perp \langle x'^2 \rangle_\perp - \langle x x' \rangle_\perp^2\right]^{1/2}$$
$$\varepsilon_y = 4\left[\langle y^2 \rangle_\perp \langle y'^2 \rangle_\perp - \langle y y' \rangle_\perp^2\right]^{1/2}$$

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

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