FAST AND ACCURATE SIMULATIONS OF 10 GeV SCALE LASER PLASMA ACCELERATORS

Jonathan Smith Tech-X UK Ltd

E. Cormier-Michel, D.L. Bruhwiler*, N. Naseri, E.J. Hallman, B.M. Cowan, J.R. Cary
Tech-X Corporation

C.G.R. Geddes, J.-L. Vay, E. Esarey, C.B. Schroeder, W.P. Leemans
Lawrence Berkeley National Laboratory

* Presently at the Center for Integrated Plasma Studies, University of Colorado Boulder

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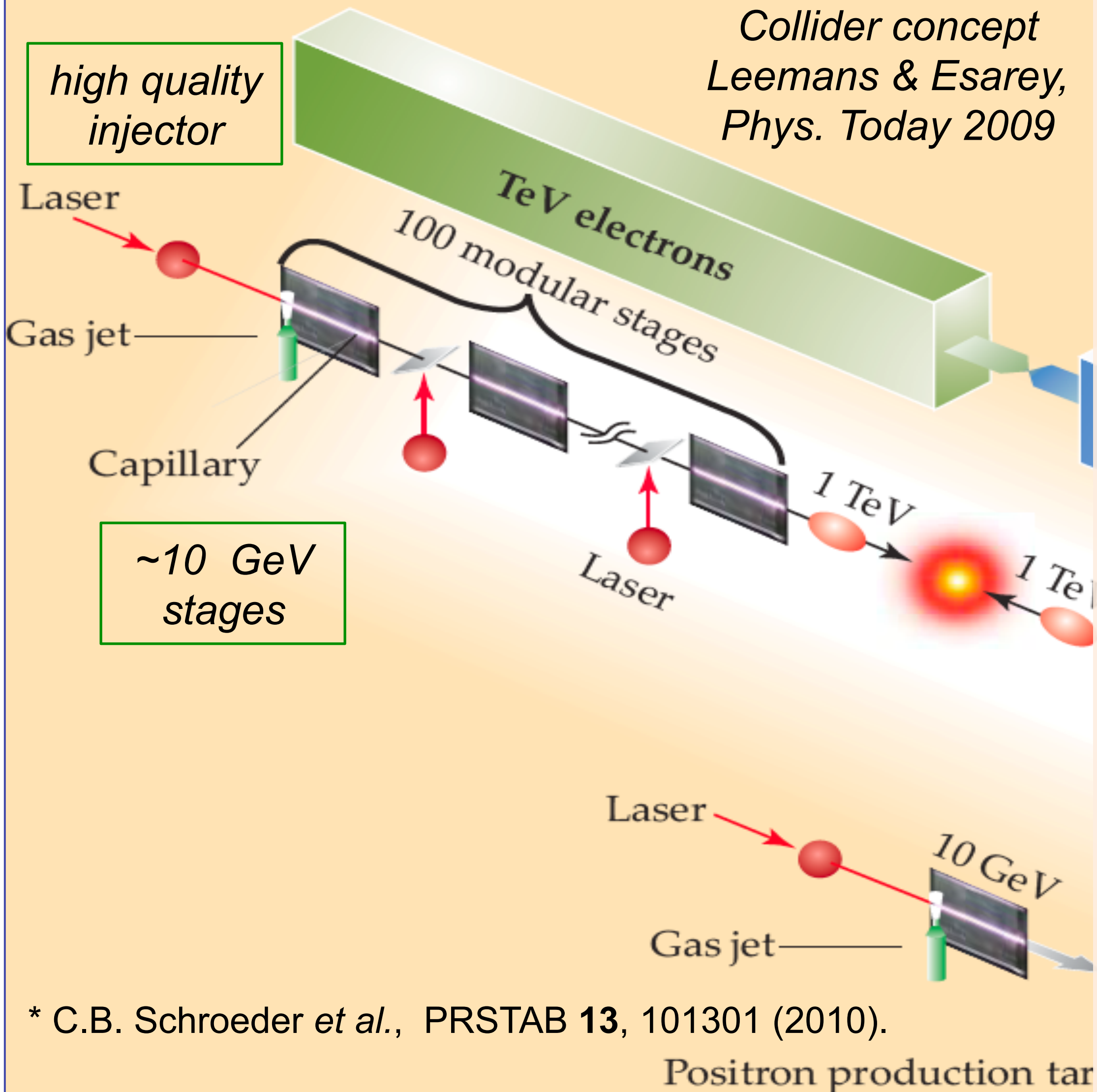
Next generation of LPA presents new challenges for simulations



Collider concept Leemans & Esarey, Phys. Today 2009

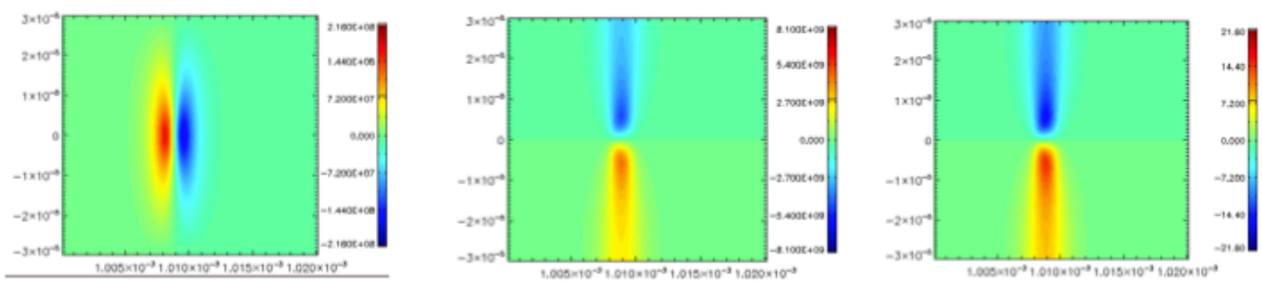
- High accelerating gradient in laser plasma accelerators allow compact devices
- For linear collider, optimal succession of 10 GeV – 1m long stages*
- Requires high quality injector
- Requires preservation of low emittance beams
- Simulations challenging because of scale separation
  - L_{acc} ~ 1 m, λ_{laser} ~ 1 μm
- Reduced models needed (envelope, boosted frame)
- Improve simulations to reduce numerical noise
  - Calculating beam self-fields with a Poisson solve in the beam frame (BFPS) allows reduce noise for low energy spread, low emittance beams

* C.B. Schroeder *et al.*, PRSTAB **13**, 101301 (2010).

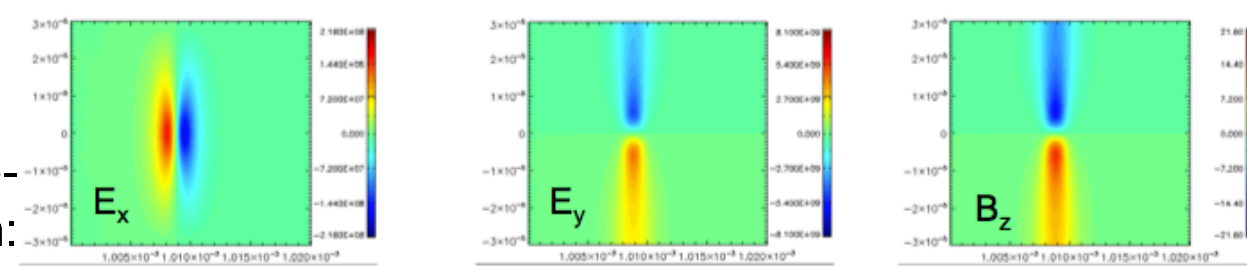
Self-fields of the e- beam can be found from a Poisson solve in the beam frame

- Very similar to what is done in tracking codes
- The beam self-fields are calculated at each time step using a Poisson solver in the frame of the moving beam
- Works for low-emittance, low divergence bunches:
  - relative motion must be non-relativistic in the beam frame
  - we refer to this as a "beam-frame Poisson solve" **BFPS** algorithm
- After 1 mm of propagation fields are consistent with the self-consistent PIC fields.

BFPS fields at 1mm:



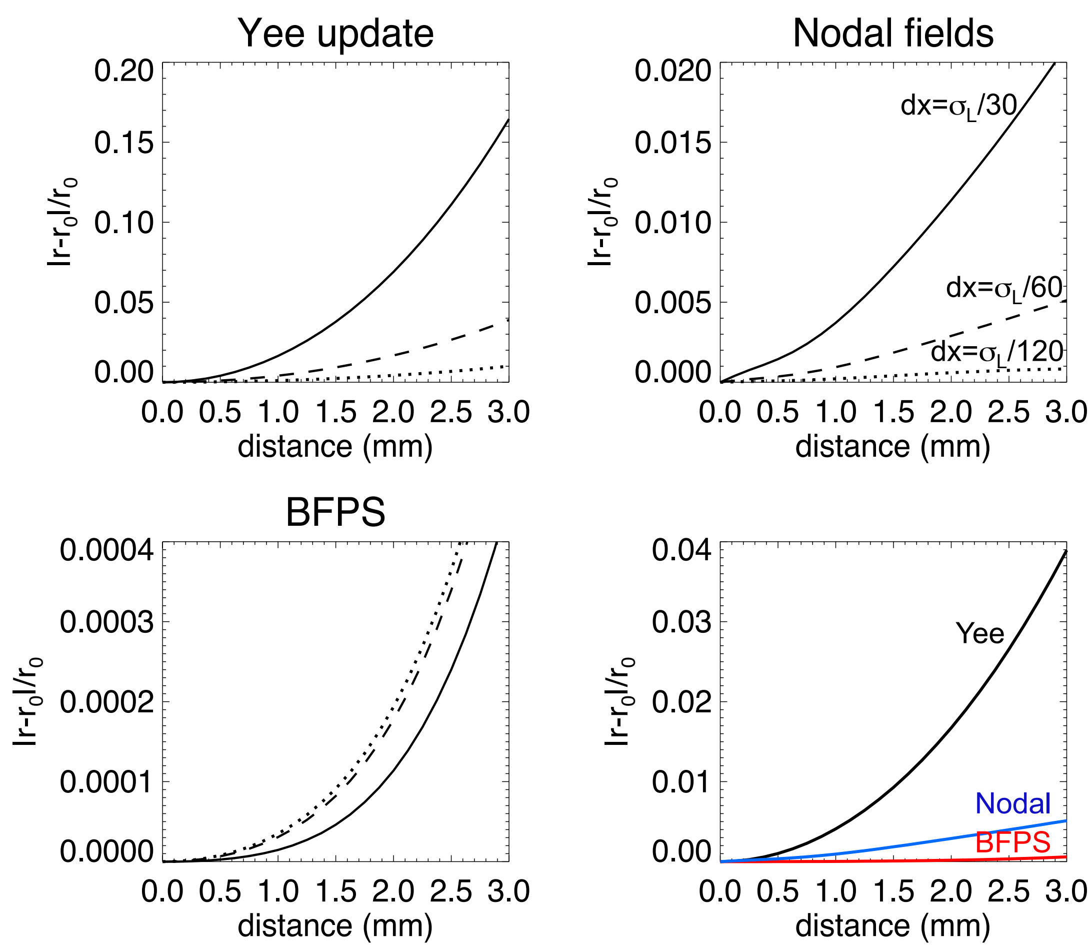
Self consistent electro-magnetic fields at 1mm:



Locating E-B fields at the nodes for update enables correct modeling of transverse forces

- Gaussian e- beam in quasi-matched linear focusing field.
- $\sigma_L = \sigma_R = 2\mu m$
- Q=113pC, E=100MeV, ε_n=0
- variable *dx*, *dy* = 4*dx*
- ~ relevant to 1GeV stage $n_0=10^{18}$ cm^{-3}
- Yee Update: usual PIC update with staggered fields
- Nodal Update: Maxwell update with E and B located at the nodes (2 cell wide stencil)*
- BFPS: the beam self-fields are calculated in the beam rest frame using a Poisson solve

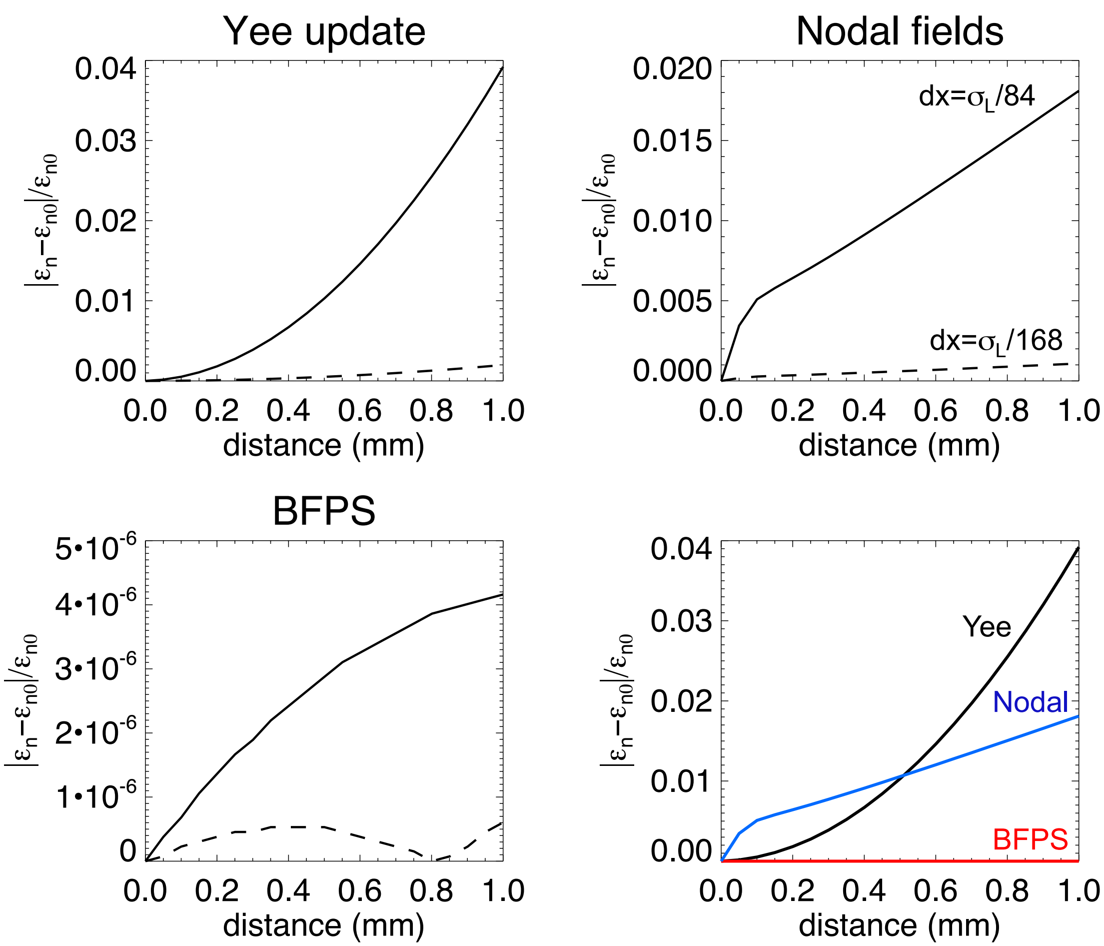
- beam density ~ $\exp(-x^2/2\sigma_L^2 - y^2/2\sigma_R^2)$



*A. Taflove and S.C. Hagness, "Computational electrodynamics", (2000)

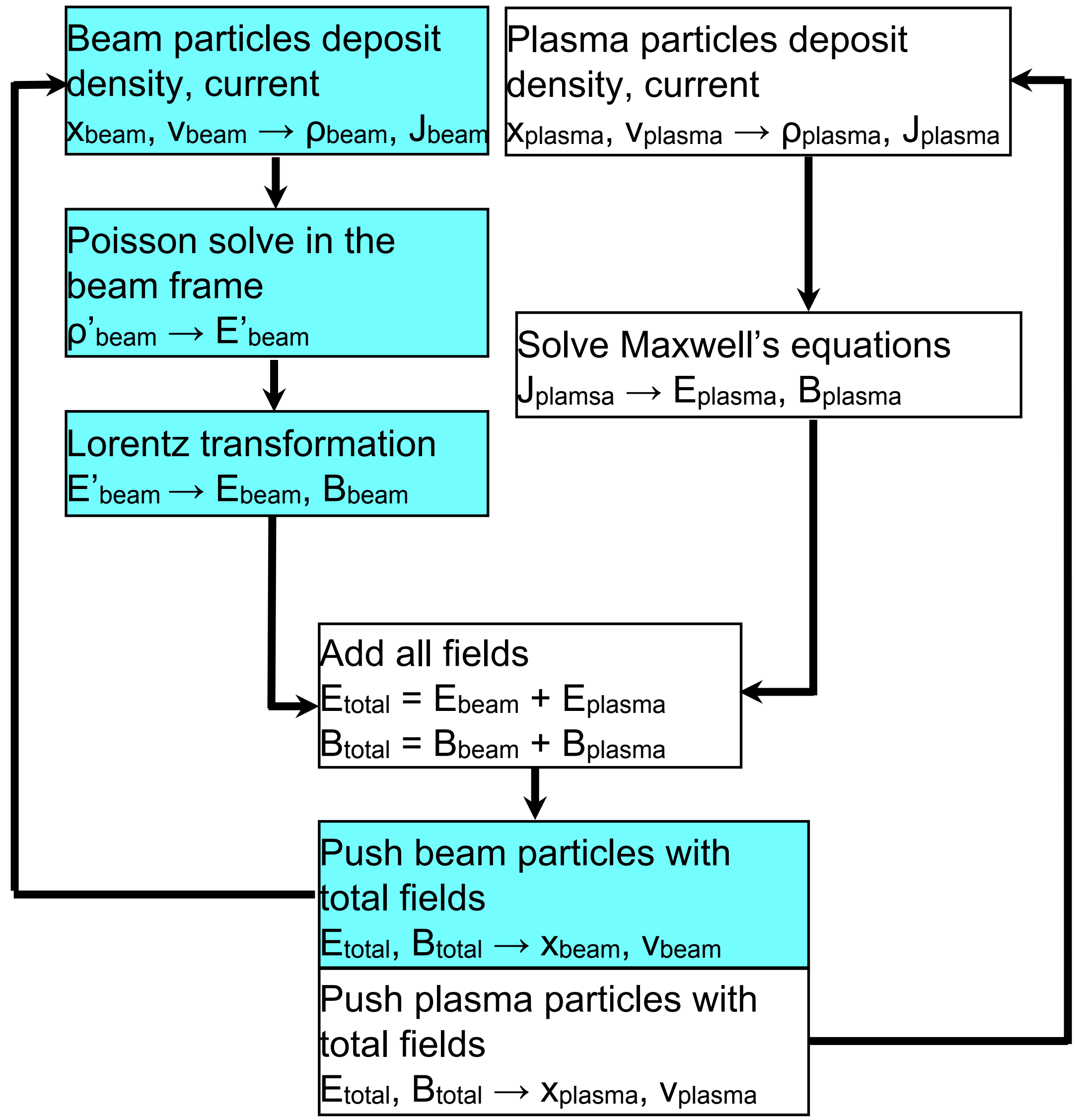
BFPS treatment of the e- beam self-fields reduces artificial emittance growth

- Gaussian e- beam in quasi-matched linear focusing field, with finite small emittance
- $\sigma_L = 8.4\ \mu m$, $\sigma_R = 16.8\ \mu m$
- Q=300pC, E=1GeV±1%, ε_n=0.01 mm mrad
- variable dx, $dy = 8dx$
- Case relevant to 10 GeV m-long stage; 10^{-3} propagation distance



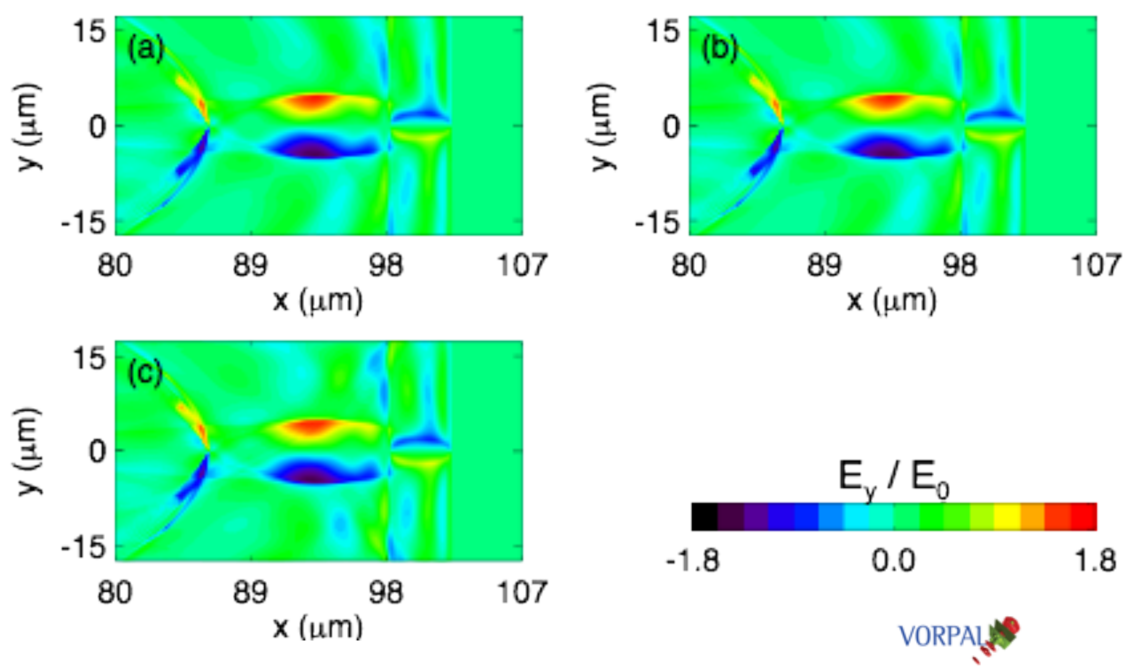
BFPS can be used inside the plasma wakefield

- Linearity of Maxwell's equation allows separate treatment of the beam in the plasma:
  - beam and plasma must be separated at time zero
  - all particles must respond to the combined fields
- For an e- beam with constant γ, the algorithm can be implemented directly from Vorpal's input file
- For e- beam submitted to acceleration, beam γ must be calculated every time step to calculate e- beam self-fields in its rest frame.



Separate beam/plasma with BFPS agrees with standard PIC

- Transverse fields when beam has propagated in the plasma
  - (a) fully self-consistent EM-PIC with Yee update
  - (b) self-consistent EM-PIC with separate sequences of updates for the beam and the plasma
  - (c) beam self-fields calculated with the BFPS



BFPS inside the wakefield prevents artificial emittance growth

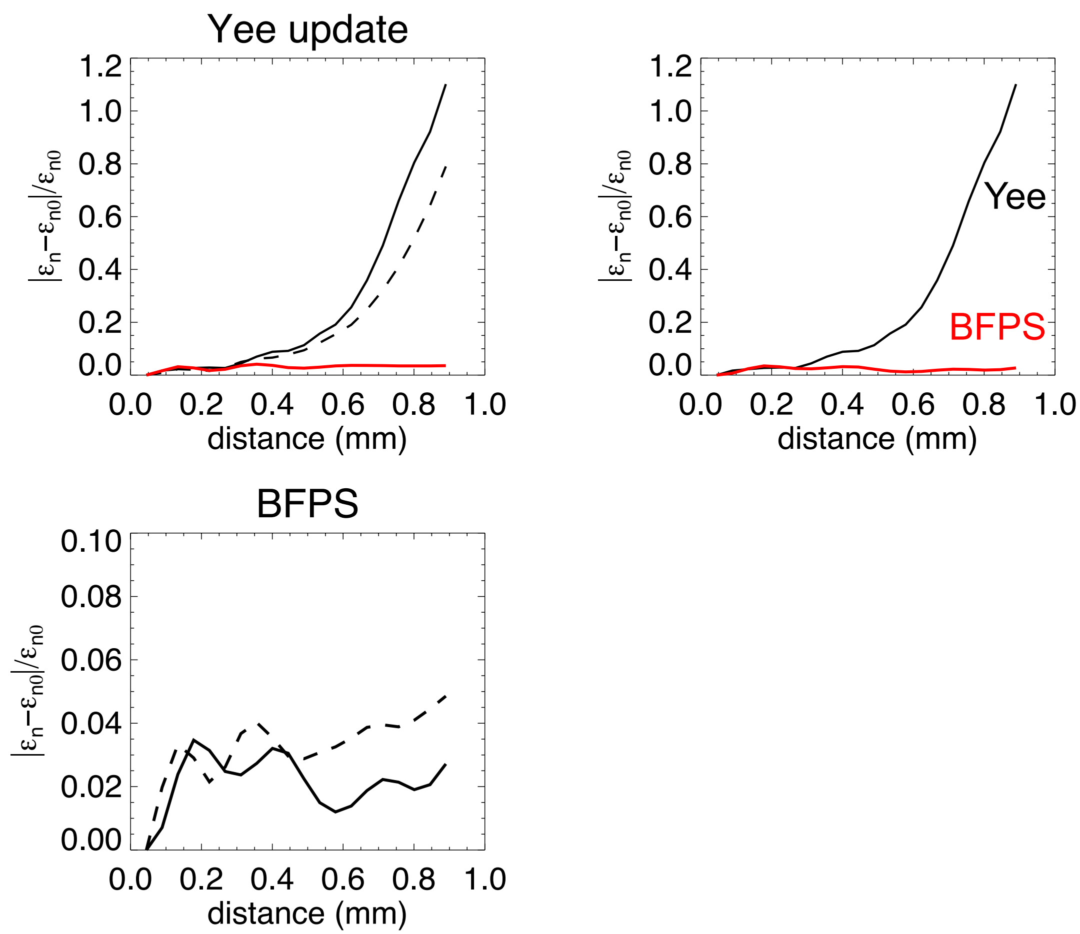
- Gaussian e- beam in plasma wakefield
- $\sigma_L = 0.17\ \mu m$, $\sigma_R = 0.6\ \mu m$
- Q=20pC, E=100MeV±1%, ε_n=0.5 mm mrad

—— $dx = \lambda_0/24 \sim \sigma_L/5$, $dy \sim \sigma_R$

λ_0 : laser wavelength

- - - $dx = \lambda_0/48$

—— $dx = \lambda_0/48$ + wide stencil current smoothing



Summary

- First implementation of “tracking code space charge algorithm” in self-consistent LPA simulations
- Very accurately models very low emittance spread relativistic bunches
  - correctly model cancelation of beam self-forces
- BFPS can be used for the bunch in self-consistent LPA simulations
- Allows correct representation of beam emittance evolution even at low resolution
- Reduced models in Vorpal (envelope, boosted frame) will allow simulation of full scale 10 GeV stages

Future developments for LPA simulations

- Fluid representation of the plasma to further reduce numerical noise
- r-z geometry to speed up simulations
- Vlasov representation of the electron beam