Architect: a 2D hybrid kinetic-fluid code for Plasma Wakefield Acceleration

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on behalf of SPARC_LAB collaboration

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Collaborators

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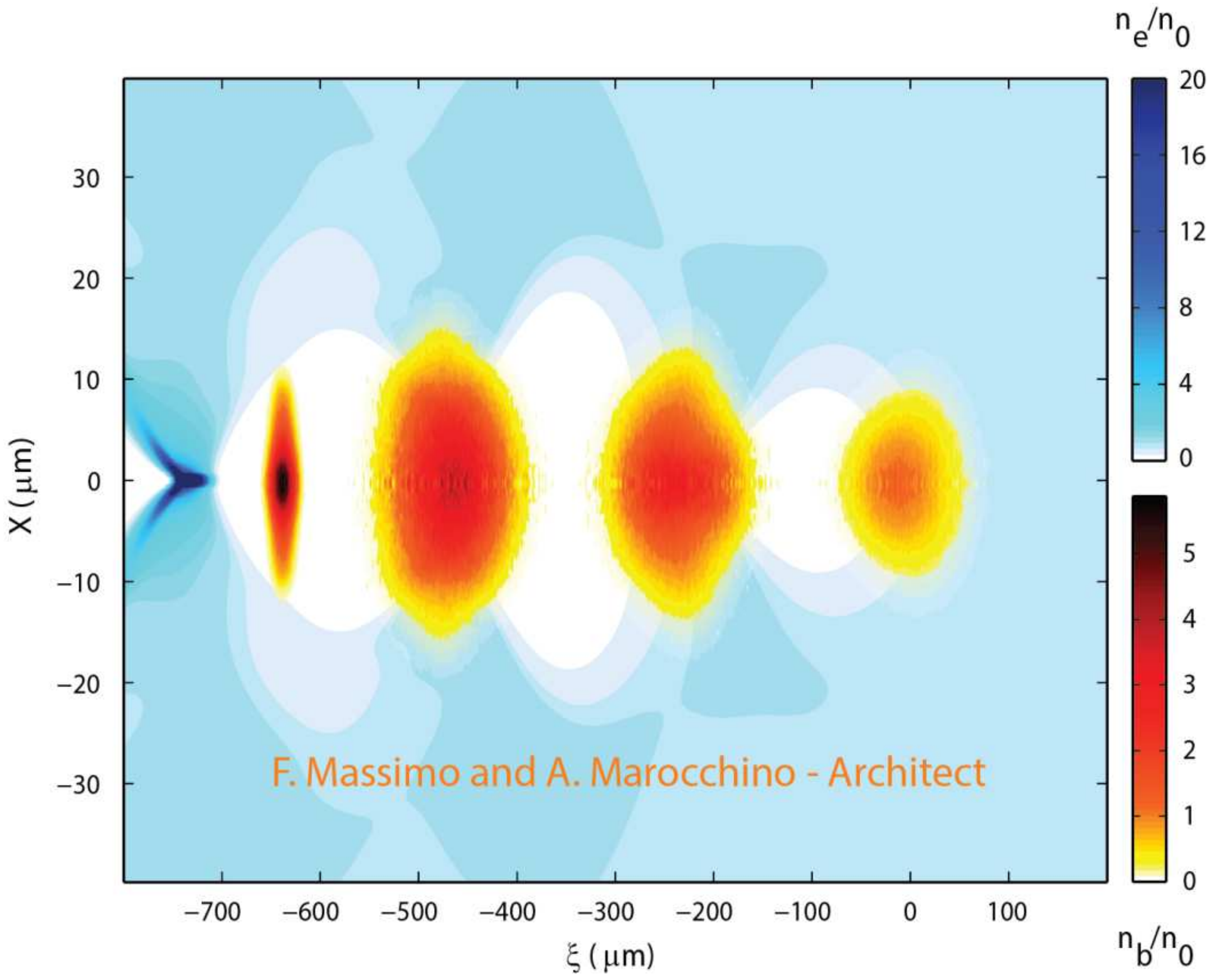
Resonant Plasma Wakefield Acceleration experiment at SPARC_LAB

Resonant excitation of plasma waves in **weakly nonlinear regime** by train of high brightness electron bunches, preserving witness **bunch quality**

Quick simulations needed for

- data analysis
- design working points
- design full PIC simulations

→ **Architect**



Architect Model

Beam particles + **Fluid plasma electron background**

$$d_t \mathbf{p}_{\text{particle}} = q(\mathbf{E}+c\boldsymbol{\beta}_{\text{particle}}\times\mathbf{B})$$

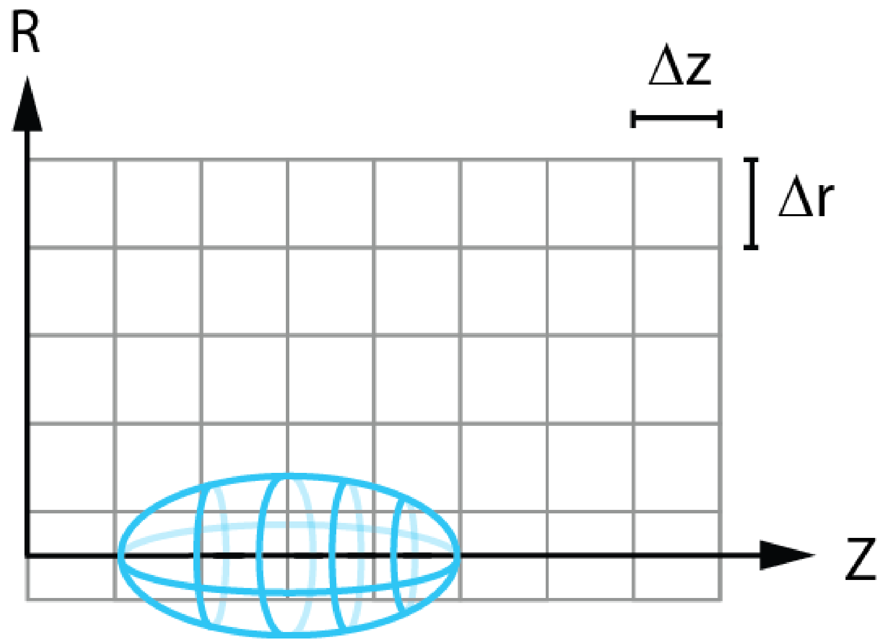
$$d_t \mathbf{x}_{\text{particle}} = \boldsymbol{\beta}_{\text{particle}} c$$

$$\partial_t n_e = -\nabla\cdot(\boldsymbol{\beta}_e c\, n_e)$$

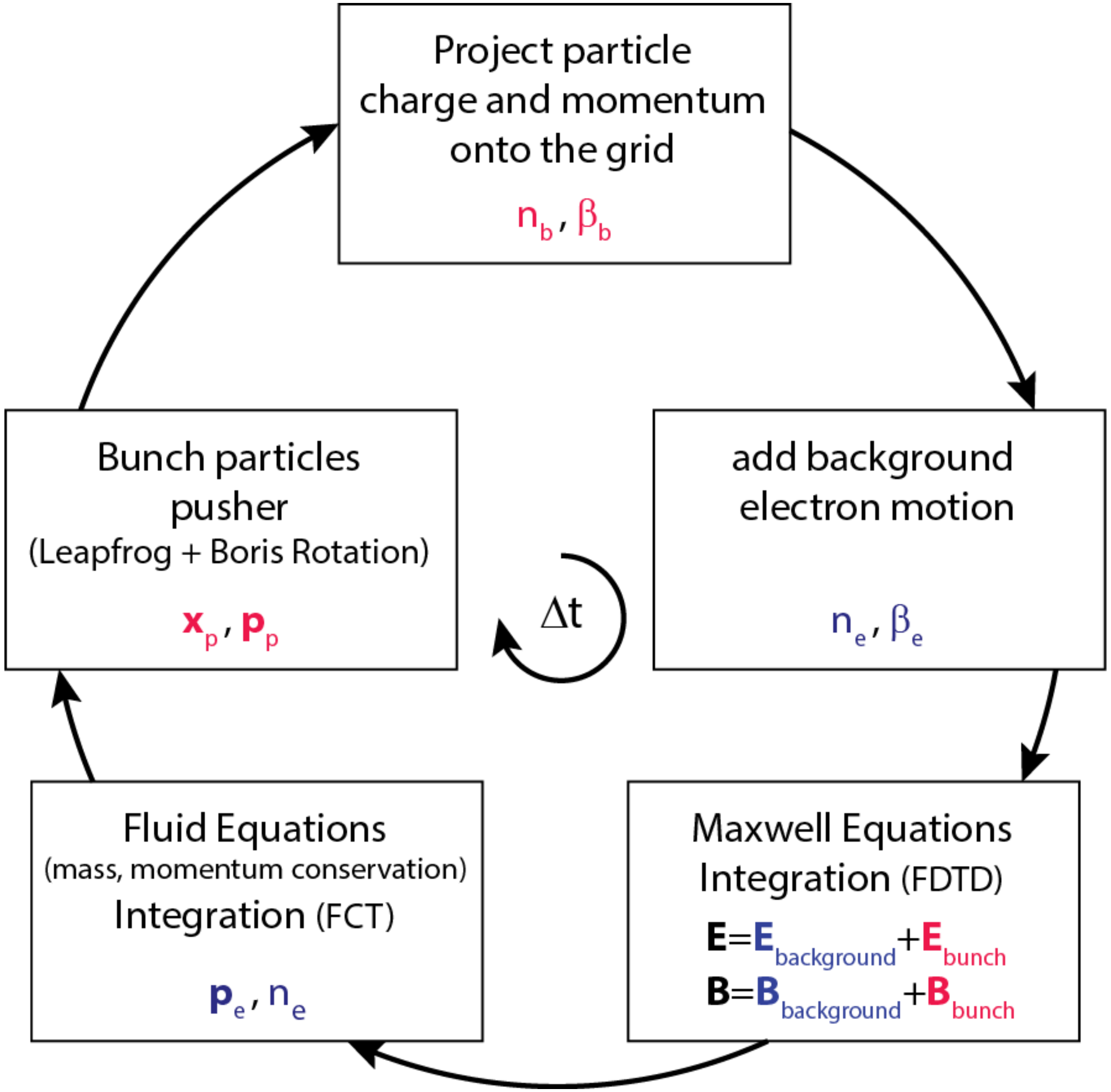
$$\partial_t \mathbf{p}_e = -\nabla\cdot(\mathbf{p}_e \otimes \boldsymbol{\beta}_e c)+q(\mathbf{E}+c\boldsymbol{\beta}_e\times\mathbf{B})$$

$$\partial_t \mathbf{B} = -\nabla\times\mathbf{E}$$

$$\partial_t \mathbf{E} = c^2\nabla\times\mathbf{B}-q\mu_0 c^3\,(n_e\boldsymbol{\beta}_e + n_{\text{b}}\boldsymbol{\beta}_{\text{b}})$$



Architect Loop



EM fields initialization

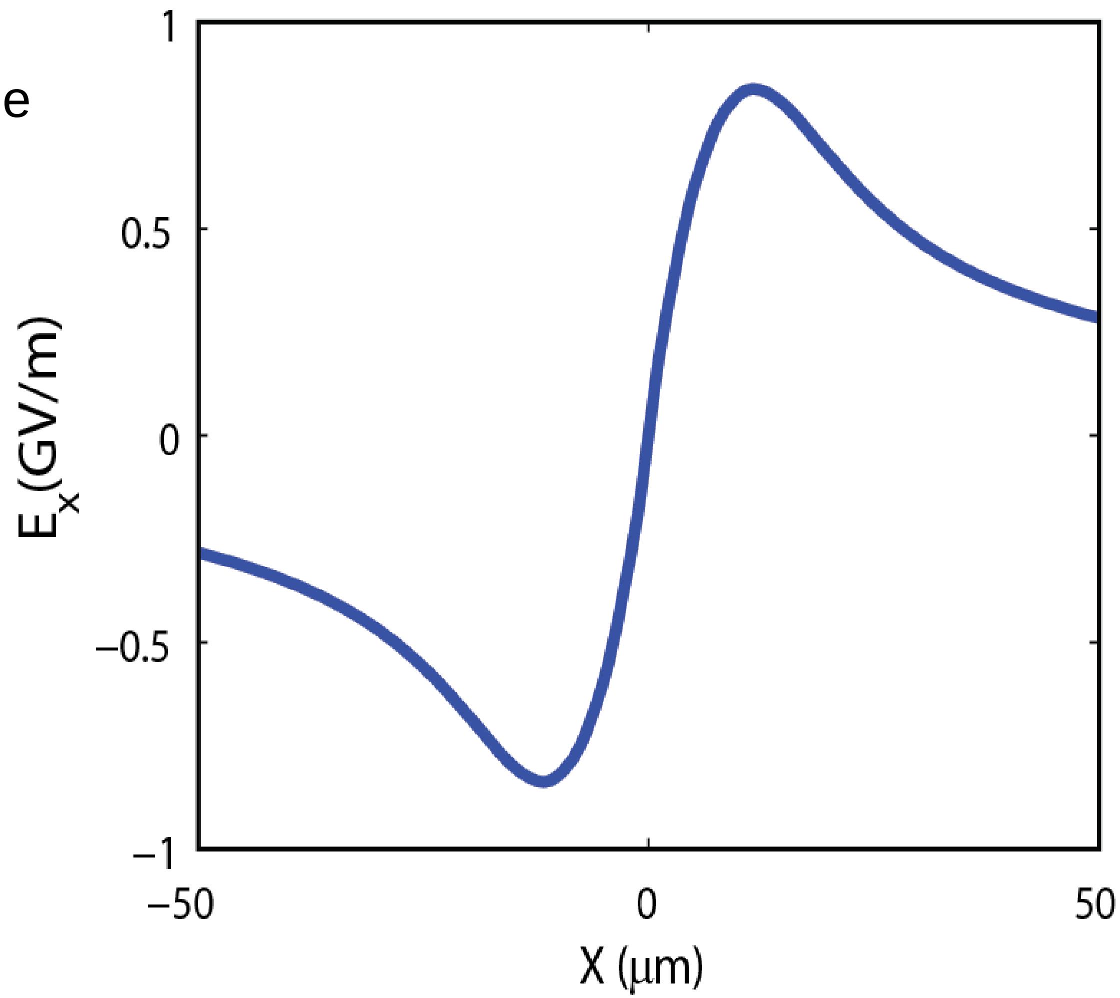
Plasma initially at rest, beam outside plasma
$\rightarrow$ Need to initialize only the beam fields in vacuum

Initialization procedure:

- solve Poisson equation in beam rest frame
- Compute fields in the lab frame

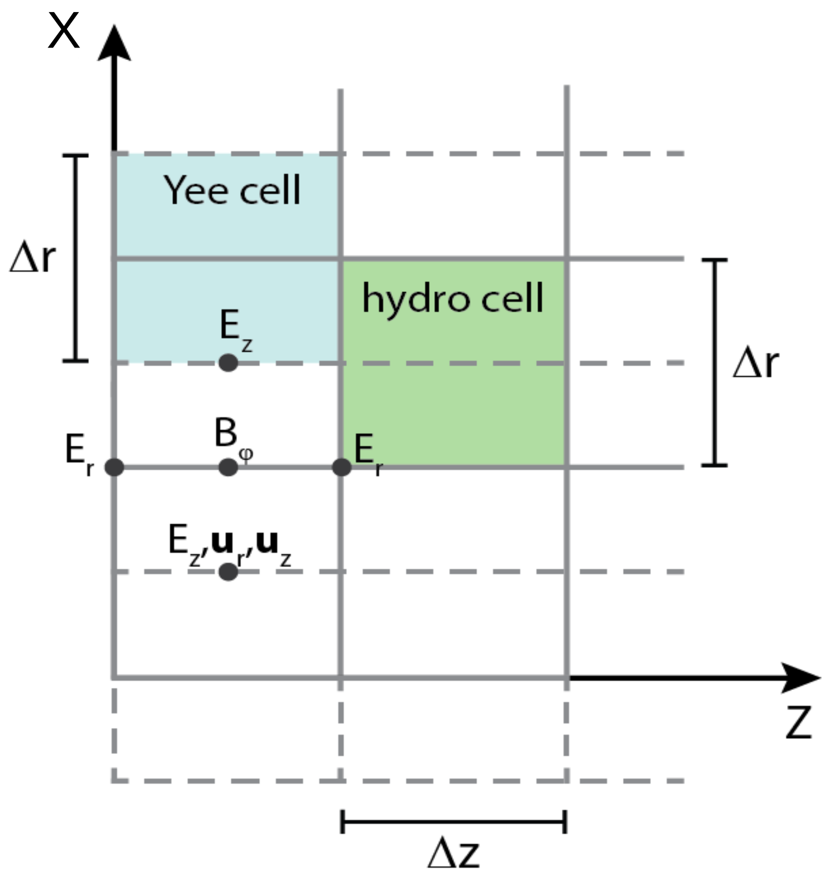
- **Very quick: 30 secs even with refined mesh**
- **No parallelization required**

T = 0, beam central section

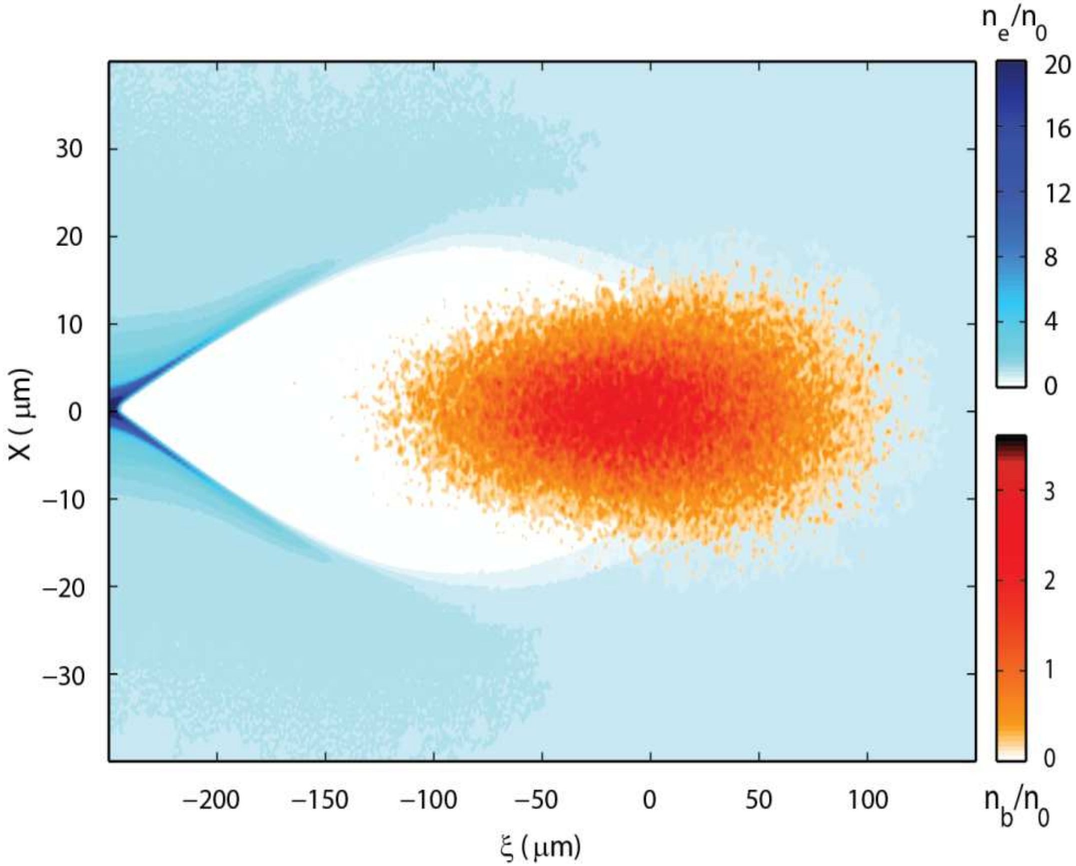


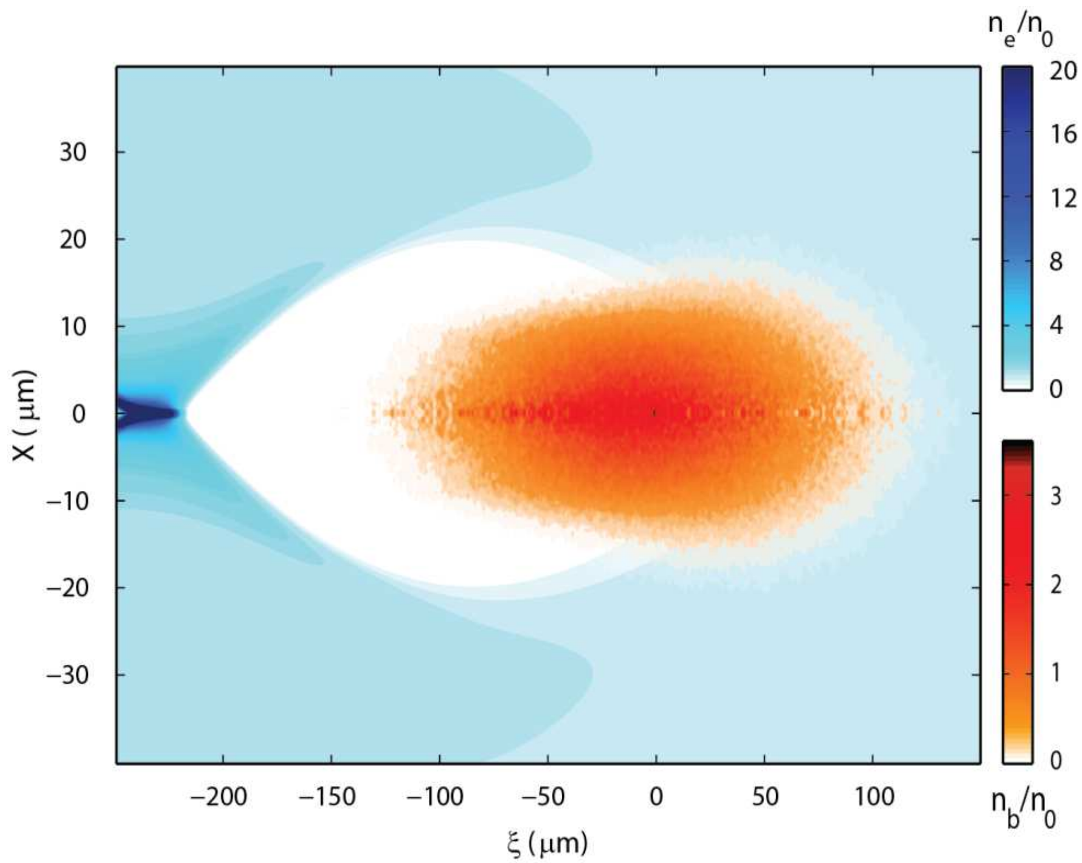
Architect Grid

- Beam moves in 6D phase space
- EM fields and fluid integration in moving window, no quasi-static approximation
- **cylindrical symmetry** assumed for fluid and electromagnetic fields symmetric BCs on axis
- Free flux BCs on the other edges
- Only X>0 domain is considered in the fluid and electromagnetic field equations



Comparison against 3D PIC code: Density





3D PIC code for the comparison: **ALaDyn**

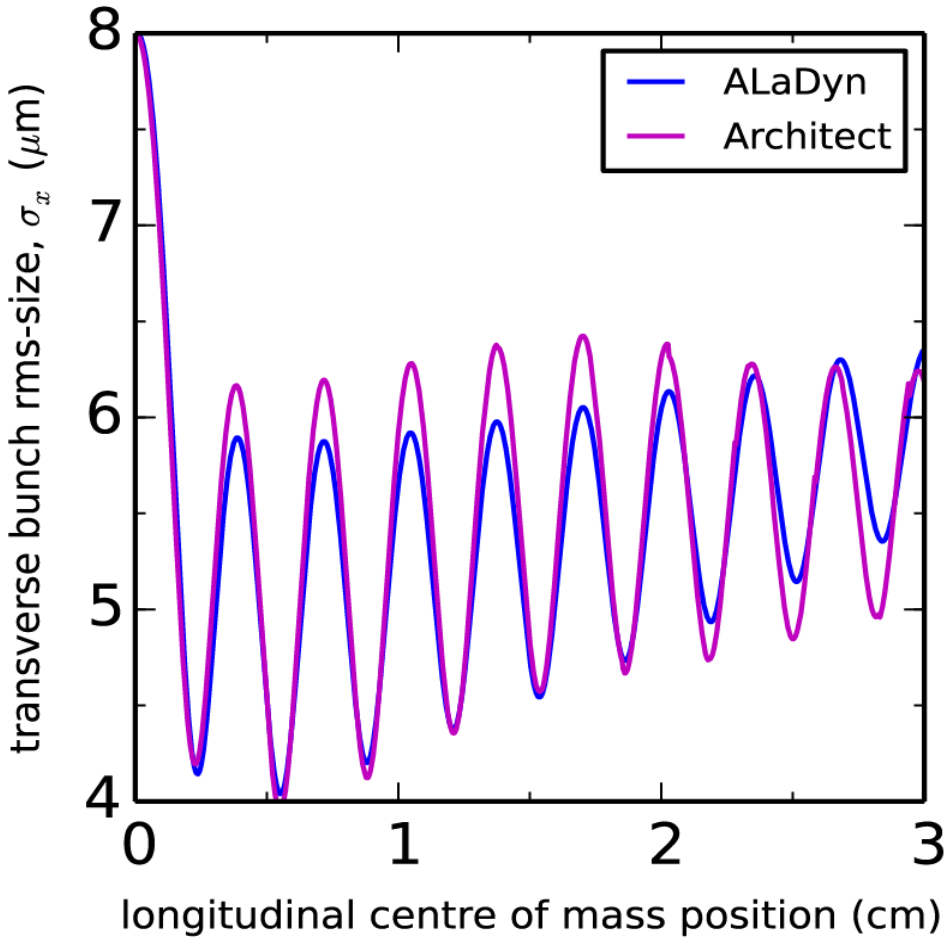
C. Benedetti et al, IEEE Transactions on Plasma Science, 34 (4), 2008

P. Londrillo et al, Nucl. Instr. and Meth. A 740, 2014

Benchmark driver parameters:

- Q = 113 pC
- σ_x = 8 μm, σ_z = 50 μm
- E_0 = 100 MeV
- ε_x = 1 mm-mrad
- $\Delta\gamma/\gamma$ = 0.1%
- n_0 = 10^{16} cm^{-3}

Comparison against 3D PIC code: Betatron oscillations



- $Q = 113$ pC
- $\sigma_x = 8\ \mu$m, $\sigma_z = 50\ \mu$m
- $E_0 = 100$ MeV
- $\varepsilon_x = 1$ mm-mrad
- $\Delta\gamma/\gamma = 0.1\%$
- $n_0 = 10^{16}\ cm^{-3}$

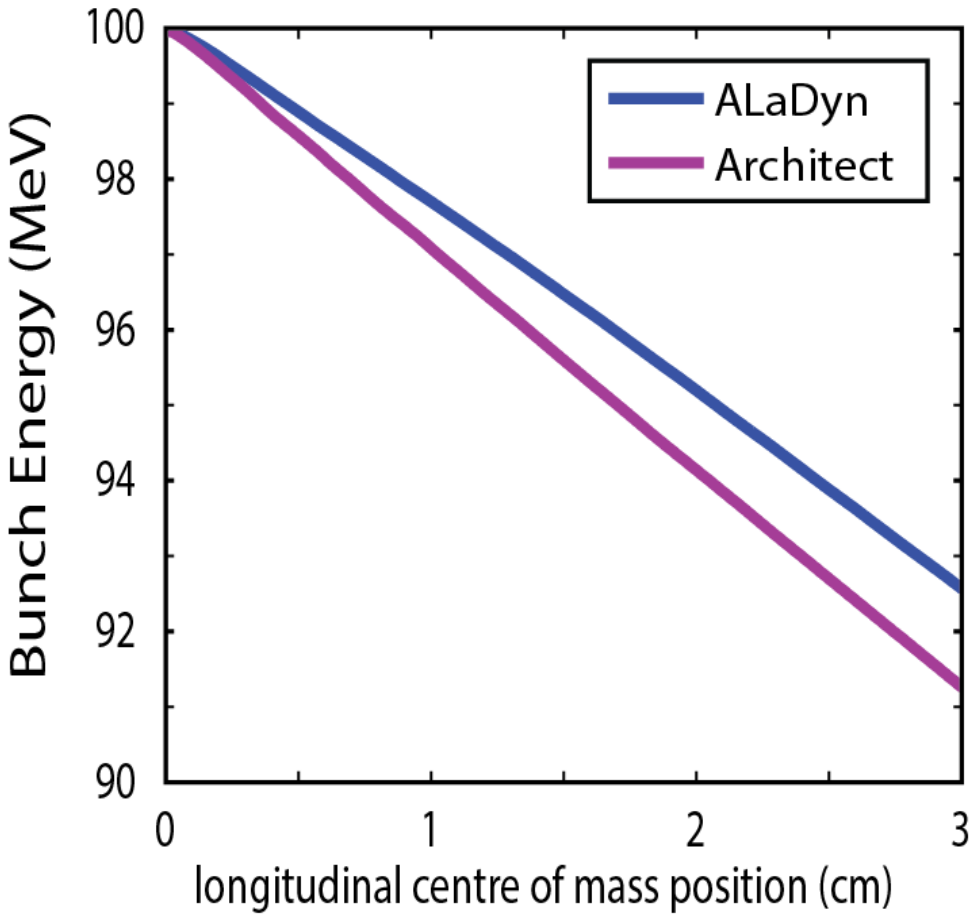
3D ALaDyn simulation

- 38 Mcells
- 300 Mparticles
- $\Delta t = 0.44$ fs
- $\Delta r = 0.4\ \mu$m
- $\Delta z = 1\ \mu$m

2D Architect simulation

- 250 kcells
- 300 kparticles
- $\Delta t = 0.44$ fs
- $\Delta r = 0.4\ \mu$m
- $\Delta z = 1\ \mu$m

Comparison against 3D PIC code: Driver depletion



- $Q = 113$ pC
- $\sigma_x = 8\ \mu m$, $\sigma_z = 50\ \mu m$
- $E_0 = 100$ MeV
- $\varepsilon_x = 1$ mm-mrad
- $\Delta\gamma/\gamma = 0.1\%$
- $n_0 = 10^{16}\ cm^{-3}$

3D ALaDyn simulation

- 38 Mcells
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2D Architect simulation

- 250 kcells
- 300 kparticles
- $\Delta t = 0.44$ fs
- $\Delta r = 0.4\ \mu m$
- $\Delta z = 1\ \mu m$

Time Scaling (1 cm)

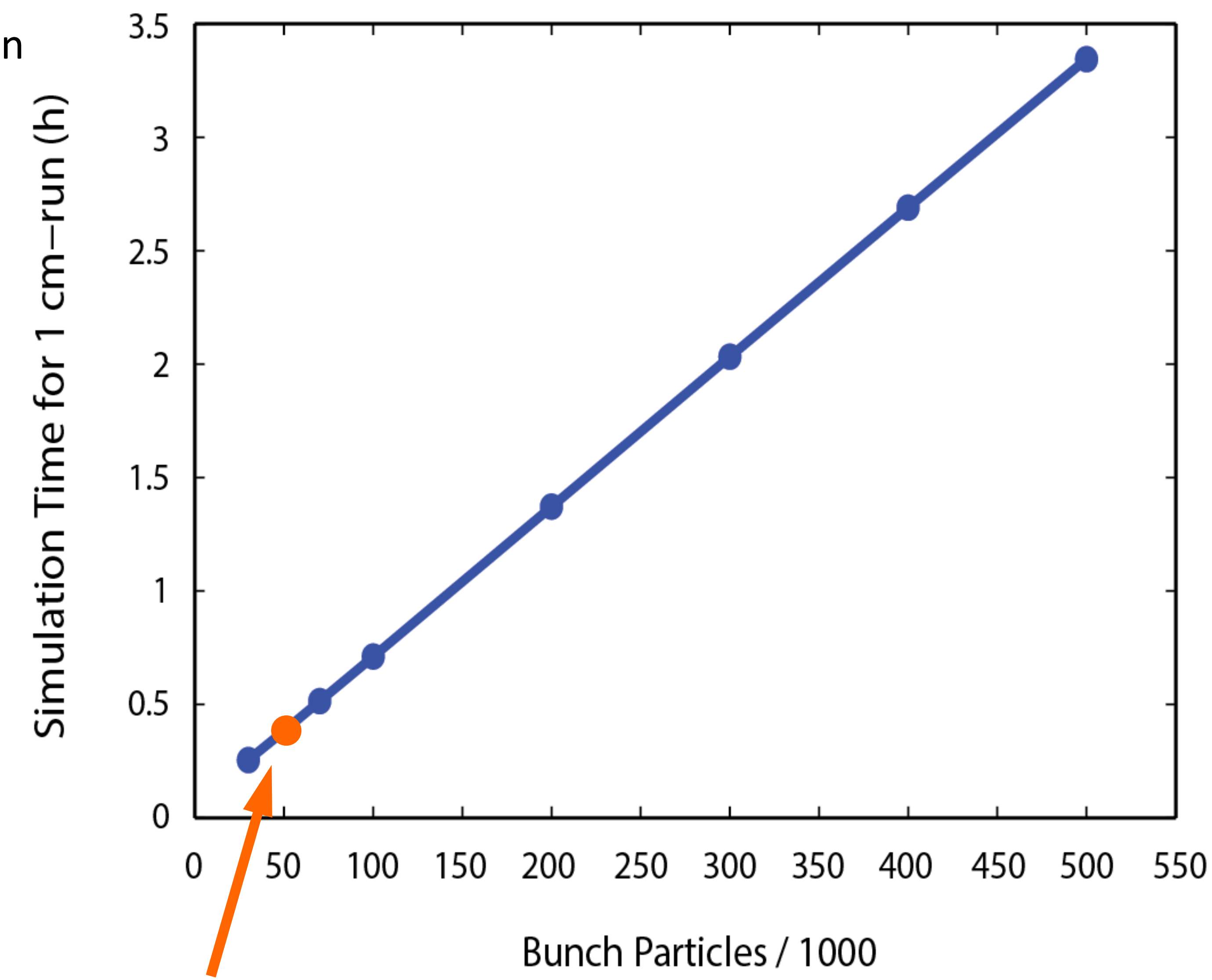
2D Architect simulation

- 200 kcells
- 300 kparticles
- Δt = 0.88 fs
- Δr = 0.8 μm
- Δz = 2 μm

3D ALaDyn simulation

- 38 Mcells
- 300 Mparticles
- Δt = 0.88 fs
- Δr = 0.4 μm
- Δz = 1 μm

~**17 kh-cores**



Fields order of magnitude and regime identification in 20 mins!

Conclusions

- Architect: 2D time-explicit hybrid kinetic-fluid code for PWFA
- Beam treated as in PIC code, relativistic cold fluid background
- Quick simulations for typical COMB scenarios of interest
- Quick, accurate beam field initialization implemented
- Good agreement with 3D PIC simulations up to weakly nonlinear regimes
- Quick tool to design experiments and full PIC simulations

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