Boosted frame PIC simulations of LWFA: Towards the energy frontier

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2 DCTI, Instituto Superior de Ciências do Trabalho e da Empresa

3 University of California Los Angeles
<table>
<thead>
<tr>
<th>Laser</th>
<th>Self-guiding</th>
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<tr>
<td>a0</td>
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<td>Spot [μm]</td>
<td>9</td>
<td>101</td>
</tr>
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<td>Density [cm⁻³]</td>
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<th>e- Bunch</th>
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<td>Energy [GeV]</td>
<td>4</td>
<td>25</td>
</tr>
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<td>Charge [nC]</td>
<td>14</td>
<td>1.8</td>
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* S. Gordienko and A. Pukhov PoP (2005)
** W. Lu et al. PR-STAB (2007)
## Motivation: Parameter range for a 300J laser

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<td>a0</td>
<td>Self Injection I*</td>
<td>43</td>
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<td>Spot [μm]</td>
<td>Self Injection II**</td>
<td>5.8</td>
</tr>
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<td>Duration [fs]</td>
<td>Self Injection II**</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>External Injection II**</td>
<td>110</td>
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Grid resolution in Laboratory and Boosted frame
Boosted Frames in LWFA simulations

Grid resolution in Laboratory and Boosted frame

Laboratory Frame

Boosted Frame

Laser
Plasma

Laser
Plasma

BOOST

S. F. Martins | Vancouver, May 2009 | PAC09
Boosted Frames in LWFA simulations

Grid resolution in Laboratory and Boosted frame

<table>
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<tr>
<th>Laboratory Frame</th>
<th>Boosted Frame</th>
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Resolution gains

- **Particles**
  - Resolution
  - Plasma contraction
- **Time steps**
  - Time step
  - Total time
- **Total**
  - $\gamma^2(1 + \beta)^2$

$\gamma = (1 + \beta)$

Moving window in Lab Frame
New Features in v2.0

- Bessel Beams
- Binary Collision Module
- Tunnel (ADK) and Impact Ionization
- Dynamic Load Balancing
- PML absorbing BC
- Optimized higher order splines
- Parallel I/O (HDF5)
- Boosted frame in 1/2/3D

osiris framework

- Massively Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium

⇒ UCLA + IST

Ricardo Fonseca: ricardo.fonseca@ist.utl.pt
Frank Tsung: tsung@physics.ucla.edu

http://cfp.ist.utl.pt/golp/epp/
http://exodus.physics.ucla.edu/
Benchmark with OSIRIS Lab

Boosted frame simulation apparatus ($\gamma = 5$)

**Plasma**
- Boost length: 0.15 cm
- Lab length: 0.75 cm
- $n_e = 1.5 \times 10^{18}$ cm$^{-3}$
- Electrons + ions
- $2.2 \times 10^9$ particles
- Quad. part. interp.

**Laser**
- $a_0 = 4.0$
- $\lambda = 800$ nm
- $\tau = 30$ fs
- $W_0 = 19.5 \mu$m

32 c/$\omega_\text{p}$
256 cells

160 c/$\omega_\text{p}$
2048 cells
Benchmark with OSIRIS Lab

Main quantities in Boosted frame

(a) Laser Electric Field

(b) Plasma Density

(c) Longitudinal Electric Field

(d) Longitudinal momentum
Benchmark with OSIRIS Lab

Energy spectrum comparison

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<td>0.6 (max)</td>
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Laboratory Frame

Region not simulated

Boosted Frame

\( \gamma = 5 \)
Benchmark with OSIRIS Lab

Energy spectrum comparison

**Laboratory Frame**

- Region not simulated

- Energy (GeV):
  - ~2.1 days in 100 CPUs (50,000 CPU.h)

**Boosted Frame**

- 20x faster in boosted frame

- Energy (GeV): (~1 day in 100 CPUs (2,400 CPU.h)

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Benchmark with experiment

Energy spectrum comparison

Experiment*

Region not simulated

Simulation in Lab Frame

Simulation in Boosted Frame

Energy [GeV]

~20 days in 256 CPUs
(122,900 CPU.h)

20x faster in boosted frame

~1 day in 256 CPUs
(6,100 CPU.h)

*Stefan Kneip et al.
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Full 3D ultra-fast boosted frame simulations for next generation lasers using OSIRIS

Self-injection: >10 GeV

External-injection: 37GeV & counting...

Longitudinal momentum

12-14 GeV beams

Laser pulse

Plasma channel

37GeV beam

Laser pulse

Distance [m]

Energy [GeV]

Initial

After 3m
Full 3D ultra-fast boosted frame simulations for next generation lasers using OSIRIS

Self-injection: >10 GeV

External-injection: 37 GeV & counting...

>300x faster in Boosted Frame

Laser pulse

Plasma channel

37 GeV beam

Longitudinal momentum

12-14 GeV beams

Distance [m]

Energy [GeV]

Initial  After 3 m

Energy Density [eV/cm]

x Lab approx [µm]

Charge Density [e/µm]

0 1 2 3 4

0 2000 4000 6000

Energy [GeV]

0 10 20 30 40

-0.14

0.14
Conclusions

- **Boosted frames can provide the means for full-PIC simulations of long-scale LWFA**
  - Laser frequency decrease: grid resolution decrease
  - Compression of rest structures: smaller simulation time

- **Good quantitative agreement for several LWFA configurations**
  - Plasma channel
  - 2GeV with External injection
  - 1.5GeV & 0.8GeV with Self-injection
  - >10GeV with Self-injection

- **OSIRIS Simulations of next generation of laser systems already suggest the parameter range for >10GeV acceleration**

Next steps

- Test higher boost velocities to achieve higher computational gains
- Further explore scheme to model next generation of LWFA experiments