In silico exploration of the most extreme scenarios in astrophysics and in the laboratory: from gamma ray bursters to ultra intense lasers

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Acknowledgments

Everyone at Work in collaboration with:

- W. B. Mori, C. Joshi (UCLA), M. Marklund (Chalmers)

Simulation results obtained at the epp and IST Clusters (IST), Dawson Cluster (UCLA), Franklin (NERSC), Intrepid (Argonne), Jugene (FZ Jülich), Jaguar (ORNL), SuperMUC (Münich), Sequoia (LLNL)
Extreme scenarios are closely associated with particle acceleration

The next generation of (plasma) accelerators [J. D. Lawson, 1983]

Unravelling collisionless shock acceleration [A. R. Bell, 1978]

W. K. H. Panofsky,
The evolution of particle accelerators and colliders

In silico experiments are critical for recent progresses

Supercomputers

’13 Peak computing power > 10 Pflop/s

Top System Performance [MFlop/s]

Source: top500.org

L. O. Silva | PRACE Days 2014 | Barcelona, May 20 201
In the project Manhattan (c. 1940) the cost of one floating point operation was \( \sim 10^{-3} \) €.

Operations performed in mechanical calculators.
Cost of labour \( \sim 4 \) €/hour, assuming one operation per second.
Total number of operation corresponding to 4 € = 1 flop/s 60 x 60 s.
Today, in a graphics processor unit each floating point operation costs $\sim 10^{-18}$ €

GPU performs 0.5 Tflop/s and costs $\sim 2000$ euros.
We assume a 3 year lifetime. Neglect the cost of electricity.
Total number of operation for 2000 euros $= 0.5 \times 10^{12}$ flop/s $\times 3 \times 365 \times 24 \times 60 \times 60$ s
Particle-in-cell simulations

Solving Maxwell’s equations on a grid with self-consistent charges and currents due to charged particle dynamics

**State-of-the-art**

\[ \sim 10^{10} \text{ particles} \]
\[ \sim (1000)^3 \text{ cells} \]

RAM \( \sim \) 1 Gbyte - 5 TByte
Run time: hours to months
Data/run \( \sim \) few MB - 10s TByte

One-to-one simulations of plasma based accelerators & cluster dynamics
Weibel/two stream instability in astrophysics, relativistic shocks, fast ignitron/inertial fusion energy, low temperature plasmas

Particle-in-cell (PIC) - (Dawson, Buneman, 1960's)
Maxwell’s equation solved on simulation grid
Particles pushed with Lorentz force
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

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http://cfp.ist.utl.pt/golp/epp/
http://exodus.physics.ucla.edu/
Scaling to 1.6 million cores

Scaling Tests

- Scaling tests on LLNL Sequoia
  4096 → 1572864 cores (full system)
- Warm plasma tests
  Quadratic interpolation
  $u_{th} = 0.1 \text{c}$
- Weak scaling
  Grow problem size
  cells = $256^3 \times (N_{\text{cores}} / 4096)$
  $2^3$ particles/cell
- Strong scaling
  Fixed problem size
  cells = $2048^3$
  16 particles / cell

F. Fiúza et al. (2013)
What challenges lie ahead?

Demonstrate 10s GeV e- with lasers and tap on the potential of conventional accelerators and plasmas to reach the energy frontier

Determine the conditions & observe Fermi acceleration by collisionless shocks in the laboratory

“Boil the vacuum”
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  *In silico* next generation of plasma accelerators

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  Gamma rays bursters and collisionless shocks in the laboratory

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Particle accelerators: rich science and applications

From compact to country size

Large

- Verified Standard Model of Particle Physics
- $W$, $Z$ bosons
- Quarks, gluons and quark-gluon plasma
- Asymmetry of matter and anti-matter
- In pursuit of the Higgs boson

Compact

- Medicine
  - cancer therapy, imaging
- Industry
  - lithography
- Light sources (synchrotrons)
  - bio imaging
  - condensed matter science

International Linear Collider

Adapted from Tom Katsouleas (Duke)
PLASMA ACCELERATORS

A new method of particle acceleration in which the particles "surf" on a wave of plasma promises to unleash a wealth of applications

By Chandrashekar Joshi
Particle acceleration in nonlinear plasma waves

Wakefield Height vs. Density modulations

“Speeding” Surfers!

Wake Driver Boat vs. Laser pulse

Why plasmas?

Plasmas do not “break” under very large electric fields

RF cavities sustain 50 MeV/m

x 20 000 for ILC

Plasmas can sustain 10’s GeV/m

Maximum accelerating electric field determined by disruption of RF cavity walls

Plasmas can sustain waves with very large electric fields with relativistic phase velocities

\[ E_0 [\text{V/cm}] \approx 0.96 \ n_0^{1/2} \ [\text{cm}^{-3}] \]

\[ n_0 = 10^{18} \ \text{cm}^{-3} \rightarrow E_0 \approx 1 \ \text{GV/cm} \]
Plasma Accelerator Progress and the "Accelerator Moore’s Law"

Current Energy Frontier

BEAM ENERGY (MeV)

YEAR


ILC
E164X
E162
RAL
RAL
RAL
LOA
LLNL
UCLA
UCLA
ANL

KEK
Osaka
LBL

Courtesy: Tom Katsouleas (Duke) / Physics Today 2004
Monoenergetic beams of self-injected electrons

2004 results confirm potential of laser-plasma accelerators

Courtesy: V. Malka (LOA), K. Krushelnick (IC/RAL), W. Leemans (LBL)
Blow-out regime of laser wakefield acceleration

Self-injection, Dephasing, and Depletion

\[ a_0 \sim 0.8 \left( \frac{\lambda}{\mu m} \right) \left( \frac{\text{Intensity}}{10^{18} \text{ W/cm}^2} \right)^{1/2} \]

- \( a_0 \) normalized vector potential of the laser [quiver momentum \( p/mc \) of e-field]
- \( W_0 \) spot size
- \( T_{\text{laser}} \) pulse duration
- Window co-moving with laser pulse @ speed of light
Can LWFA reach the energy frontier with the next generation of lasers?

Next generation of lasers @ 10+ PW

Overall 10PW Schematic

Vulcan Laser Facility
- USER Facility
- 8 Beam CPA Laser
- 3 Target Areas
- 3 kJ Energy
- 1 PW Power

- Will be based on a combination of LBO and KD*P
- 3 stages of amplification
- Very high contrast source
+40GeV with externally injected beams

Tailored injected beam to minimize final energy spread

Guiding channel
Length: 5.28 m
Density: 2.210^{16} \text{ cm}^{-3}

Stable accelerating field for over 5 meters

40GeV beam

Applications for LWFA beams

HEP Collider & radiation

- E > 10 GeV
- B ~ 1 T
- 1 km
- 100 m
- 1 cm

Light Sources (FEL)

- Plasma based
  - Ultra short accelerating structure
- Undulator like motion in ion channel
Probing before destroying

Ultra intense x-ray sources will allow for imaging of larger systems with unprecedented contrast/resolution

Ultra fast fs sources allow for x-ray bioimaging

Demonstration at LCLS

Single mimivirus particles intercepted and imaged with an X-ray laser


Most exciting advances are (still) with beam drivers
Self-modulated proton driven accelerator

10 cm proton bunch
- $\sigma_r = 200 \, \mu m \sim c/\omega_p$
- $\sigma_z = 10 \, cm \sim 600 \, c/\omega_p$
- $N_p = 10^{11}$ particles
- 500 GeV

Test electron bunch

5 m plasma source
- $n_0 = 10^{14}-10^{15} \, cm^{-3}$
- $L_p = 5-10 \, meters \sim 10^4 \, c/\omega_p$

Proton beam dump

Self-modulated bunch*

Accelerated electrons

Spatial-temporal SMI theory
N. Kumar et al PRL 104 255003 (2010)

Wake phase velocity during SMI growth
C. Schroeder et al PRL 107 145002 (2011)

Wake phase velocity after SMI saturation
A. Pukhov et al PRL 106 145003 (2011)
Beam instabilities are critical to form accelerating structure


Self-modulation instability
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Colliding flows of plasmas are pervasive in astrophysics

**Gamma Ray Bursters**

**Pulsar Wind Nebulae**

**Supernova Explosion**

**Cassiopeia A**
X-ray: NASA/CXC/SAO; Optical: NASA/STScI; Infrared: NASA/JPL-Caltech

The landscape of collisionless astro/space shocks

\[ \sigma \equiv \frac{B^2}{4\pi(\gamma - 1)nmec^2} = \left(\frac{\omega_c}{\omega_p}\right)^2 \left(\frac{c}{v}\right)^2 \]

Adapted from A. Spitkovsky
Collision of two relativistic plasma slabs

Simulation apparatus

Wall reflection + Shock formation

“Cold” plasma
\[ \gamma = 20 \]

- Gamma = 20
- Electrons + ions
- \[ m_i = 32 m_e \]
- 1x2 particles per cell

286 \( c/\omega_{pe} \)
2560 cells

1565 \( c/\omega_{pe} \)
14000 cells

Shock formation and evolution

Ion density

Time = 3525.00 [1/\omega_p]

Shock structure and jump conditions verified

Ion density and shock profile

![Graph showing ion density and shock profile with density filaments and shock front highlighted.]

Mathematical expression:

\[
\frac{n_2}{n_1} = \frac{\Gamma_{ad}}{\Gamma_{ad} - 1} + \frac{1}{\gamma_0 (\Gamma_{ad} - 1)} \approx 3.13
\]
Relativistic fireballs in the laboratory

Configuration for e-e+ overlap and fireball generation

29 GeV electron and positron bunches
\( \sigma_x = \sigma_y = 2\sigma_z = 20 \ \mu m \)
Emittance = \( 10^{-5} \) mrad

Dephasing technique to overlap beams
Typically used in PWFA to reduce bunch distance to ~100 microns

20 cm plasma
\( n_e = 2.7 \times 10^{17} \ \text{cm}^{-3} \)

Probing magnetic fields

Faraday Rotation

X-ray Diagnostic

Schlieren

Polarized Laser Beam

Magnetic Spectrometer

N. Shukla et al, in preparation (2014)
Beam filamentation and B-field generation

Beam filamentation & B-field generation with 29GeV fireballs @ SLAC


Reproducing GRB like shocks in lab

Numerical Parameters
- \( D_x = D_y = 0.25 \frac{c}{W_{pe}} \)
- 64 particles per cell
- \( 10^9 \) particles
- cubic interpolation

Physical Parameters

Laser
- \( \lambda_0 = 1 \mu m \)
- \( I_0 = 10^{20} - 10^{22} \text{ Wcm}^{-2} \)
- \( \tau_0 = 1 \text{ ps} \)

Plasma
- \( L = 20 \times 100 \mu m^2 (W_{pi}^2) \)
- \( n_{e0} = 10 n_c - 100 n_c \)
- \( m/m_e = 1836 \)
Collisionless shock launched with ultraintense laser
Similar underlying physics/results in 3D
Electrostatic shocks can be generated in the laboratory.

D. Haberberger et al., Nature Physics, January 2012

Shock wave acceleration of protons in near-critical density targets

D. Haberberger et al., Nature Physics, January 2012
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The quantum vacuum and pair production with intense fields

Intensities required to start to probe the quantum vacuum are within reach

Strong debate about this transition: $10^{24} \text{ W/cm}^2$ or $10^{26} \text{ W/cm}^2$

Work done by the electric field over a Compton wavelength > electron rest mass determines the Schwinger field

QED at ultra high intensities is almost unexplored*
QED cascades in counter propagating lasers

Parameters
- absorbing boundaries
- $a_0 = 1000$
- $\lambda_0 = 1 \mu m$
- Linear polarization
- $W_0 = 5 \mu m$
- $\tau = 30$ fs
QED cascades in counter propagating lasers

T. Grismayer et al., in preparation, 2014

Cascades
time = 127.88 [1/\omega_p]

- photons
- positron
- electron

QED cascades in counter propagating lasers + B field

B orientation determines dynamics of pair plasma

Parameters
- absorbing boundaries
- $a_0 = 700$
- $\lambda_0 = 1 \mu m$
- Linear polarization
- $W_0 = 10 \mu m$
- $\tau = 30 \text{ fs}$
- $B_0 = 3 \text{ G Gauss}$

T. Grismayer et al., in preparation, 2014
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In silico experiments critical for the design of new experiments, facilities, and triggering progress in many topics in particle acceleration

Fundamental algorithms for particle-in-cell simulations provide an excellent testbed for the exascale computing challenges