Ultra-intense laser-plasma interactions with the BELLA-i PW user facility

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Frontiers of Plasma Science Town Hall, Bethesda MD

June 30 – July 1, 2015
BELLA: the highest rep rate PW-laser in the world for laser plasma acceleration experiments

- Unique tool for development of 10 GeV laser plasma accelerator and other collider relevant concepts

- First commercial Petawatt laser operating at > 42 J in ~30 fs at 1 Hz

Top 10 American Physical Society 2014 News
Top 20 Scientific American 2014 list
NERSC 2015 Award for High Impact Scientific Achievement
Present BELLA PW laser and long focal length beamline

BELLA currently has one beamline
- Long focal length
- Goal: 10 GeV module
Laser quality and experienced operations team are key to successful experimental campaigns

- Experienced team
  - High mode quality
  - Pointing stability
  - Know-how in handling high peak power

- Important improvements:
  - Pulse shaper
  - Ultra-stable oscillator and regenerative amplifier pump
    - 30 TW/J w/ Dazzler

- Development of 10 GeV module
- Collider relevant concepts
- Accelerator stewardship
BELLA-i beamlines: expand the facility by adding short focal length capability – ultra-high intensity
For electron acceleration, BELLA is focused with long focal length. For ions (etc.) it requires short focal length and plasma mirrors.

**Electron acceleration**

- Intensity: $\sim 1.5 \times 10^{19}$ W cm$^{-2}$
- Acc. fields: $\sim 10$-50 GV/m
- 13.5 m focal length
- 55 micron spot

**Ion acceleration**

- Intensity: $\sim 3-5 \times 10^{21}$ W cm$^{-2}$
- Acc. fields: $\sim$ TV/m
- <1 m focal length
- 4-5 micron spot

Plasma mirror technology for contrast clean-up
BELLA-i beamlines: expand the facility by adding short focal length capability – ultra-high intensity
Ion Acceleration
High intensity BELLA-i allows study of different ion acceleration mechanisms

MVA
Laser: High Intensity
Target: Near Critical Density slab
Ion Energy: hundreds of MeV to GeV

RPA & CE
Laser: High Intensity
Target: Thin solid density foils
Ion Energy: hundreds of MeV

TNSA
Laser: Low Intensity
Target: Thick solid density foils
Ion Energy: ~100 MeV

Applications: Radiography, Deflectometry, Cancer Therapy, Injection into conventional accelerators, Fast Ignition, Isochoric heating of matter, Positron Emission Tomography, Nuclear Physics…
Target Normal Sheath Acceleration: optimal for low intensity and thick targets

The TNSA ion energy scales as

\[ T_{e,h} = m_e c^2 \sqrt{1 + a_0^2} \]

where

\[ a_0 = \left( \frac{eE}{m_e c} \right) = \sqrt{\frac{I^2}{1.37 \times 10^{18}}} \ W/cm^2 \]


Normal Sheath Acceleration
- Poor contrast requires thick target
- Prepulse creates preplasma on surface
- Pulse drives some e\textsuperscript{-} through target
- Charge separation at rear accelerates protons

The TNSA ion energy scales as

\[ T_{e,h} = m_e c^2 \sqrt{1 + a_0^2} \]
Radiation Pressure Acceleration requires high intensity and high contrast laser pulses

\[ E_{\text{ref}} = \frac{E_{\text{in}}}{4} \]

\[ E_{\text{foil}} = E_{\text{in}} \, 1 - \frac{1}{4} \frac{2}{w+1} \]

In the nonrelativistic regime:

\[ E \sim w^2 \]

Normalized laser fluence

The ion momentum scales as

\[ \frac{p_\alpha}{m_p c} = \frac{2w(w+1)}{2w+1} \]

Radiation Pressure Acceleration Regime

- High contrast allows the interaction of non-expanded target with the main laser pulse
- Pulse is reflected by the target
- The target is accelerated by the radiation pressure

Coulomb Explosion: High Intensity Laser Pulse is Able to Evacuate All the Electrons from the Target

\[ \mathcal{E} \sim P^{1/2} \]

\[ a = \frac{n_e}{n_{cr}} \cdot \frac{l}{L} \]

Coulomb Explosion Regime
- High contrast allows sub-micron target which become transparent to laser
- Pulse propagates through target
- Removes most electrons from target
- Much larger charge separation at rear
- Best designs use high-Z/low-Z layers

Magnetic Vortex Acceleration generates ion beams from near critical density plasma slab

Magnetic Vortex Acceleration Regime
- Target – plasma slab of near critical density with thickness much larger than the laser pulse length
- The pulse propagation inside the target generates a channel in electron and ion densities as well as strong moving electric and magnetic fields
- Upon exiting the plasma the magnetic field generates a quasi-static electric field that accelerates and collimates ions from a thin filament formed in the propagation channel

The maximum ion energy scales as

\[ E_i = m_e c^2 2^{2Z_i/n_{cr}} \frac{n_e}{n_{cr}} \frac{R_{ch}}{\mu} P^{2/3} \]

High intensity BELLA allows study of different ion acceleration mechanisms: up to 1 GeV

- **High power:** 30 J, 30 fs
- **High contrast:** $10^{10} - 10^{12}$
- **Tight focusing:** $f/D = 1 - 4$
- **High Intensity:** $I = 10^{21} - 10^{22}$ W/cm²

**MVA**
- Laser: High Intensity
- Target: Near Critical Density slab
- Ion Energy: hundreds of MeV to GeV

**RPA & CE**
- Laser: High Intensity
- Target: Thin solid density foils
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**TNSA**
- Laser: Low Intensity
- Target: Thick solid density foils
- Ion Energy: ~100 MeV
Electron Acceleration:
Highly Nonlinear Wakefields
Electron acceleration: BELLA-i allows access to highly nonlinear wake regimes

- **Blowout regime**
  - $a_0 \gg 1$
  - Very asymmetric
    - Focuses e-
    - Defocuses e+
  - Self-trapping
  - Self-guiding
  - Highest fields

- **Quasi-linear**
  - $a_0 \sim 1$
  - Symmetric e+/e-
  - Dark current free
  - Channel required
  - Tailor focusing forces via laser profile
High Intensity Laser Generates Nonlinear Bubble Wakes in Underdense Plasmas

3D PIC simulation

Bow wave

TWB

2nd cavity

1st cavity

Laser pulse

Laser-induced modulation

Bow wave

Cavity wall

Cavity

Laser

Laser pulse $a_0=6.62$

$10\times10\times10\mu m^3$

Linearly polarized (y-axis)

Plasma $n_e = 1.14\times10^{18} \text{ cm}^{-3}$

High Harmonics Generation by Electron Density Cusps Oscillating in Laser Field

Source of high harmonics
(EM energy density for $\omega \geq 4\omega_0$)

3D PIC simulation

(a) The electron density (blue), laser envelope (curves for $a = 1, 4, 7, 10$), and electromagnetic energy density, $W_H$, for frequencies from 60 to 100 $\omega_0$ (red).

(b) The upper spike emission spectrum for the dashed rectangle in (a).

(c) The electron density profile 10 laser cycles earlier than (a) and the right spike structure (d).

Flying Mirrors
Electromagnetic Pulse Intensification and Shortening by Flying Mirror formed in laser-plasma interaction

Double Doppler Effect
A. Einstein, Ann. Phys. (Leipzig) 17, 891 (1905)

Paraboloidal relativistic mirrors are formed by the wake wave left behind the laser driver pulse

Theory

Paraboloidal relativistic mirrors are formed by the wake wave left behind the laser driver pulse

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Spherical Plasma Wave Acting as a Spherical Flying Mirror Focuses the Intensified Pulse

\[ I_r \sim 4 I_0 \]

\[ I_0 = \frac{W_0}{\pi R^2 \tau} \]

\[ R = \frac{\lambda}{2\pi \Delta} \]

\[ R' = \frac{\lambda'}{2\pi \Delta} \]

is the Lorentz factor of the spherical plasma wave

Flying Mirrors are Generated using the Laser Driven Ion Acceleration Setup

Flying Mirror from Coulomb Explosion

V.V. Kulagin, et al., Phys. Rev. Lett. 99, 124801 (2007);
D. Habs, et al., Appl. Phys. B 93, 349 (2008);

Flying Mirror from Radiation Pressure Acceleration


Flying Mirror from multiple electron layers
(Directed Coulomb Explosion)

High Intensity Particle Physics
Nonlinear QED
High Intensity Particle Photon Interactions

- Nonperturbative Quantum Field Theory
- Matter in extreme conditions
- Electromagnetic Cascades
- Electromagnetic Avalanches
- Ultimate Laser Intensity Limit
- Next generation lasers:
  - day-to-day operation
  - new laser-matter interaction applications
- Future γγ colliders
- Future lepton colliders
- Various astrophysical phenomena
Electromagnetic cascades: high event rates for PW lasers colliding with e-beams

Multiphoton Compton effect

Multiphoton Breit-Wheeler effect

BELLA-i facility provides high intensity laser beamlines enabling a wide range of frontier plasma science

- Build a short focal length beamline on BELLA with plasma mirror and diagnostics to enable high intensity laser-matter experiments
  - Complements present long focal length beamline for electron acceleration experiments
  - Plasma mirror technology is routinely used on staging experiment and will enable access to unprecedented clean interaction physics

- Enables laser-driven frontier plasma science
  - Ion acceleration in various regimes
    - RPA: compete acceleration of very thin foils (>100 MeV)
    - MVA: acceleration in near-critical plasmas (approach 1 GeV)
  - Ion beams for warm dense matter, medical applications, etc.
  - Nonlinear plasma wakes, bow waves, high harmonics, flying mirrors
  - Nonlinear QED, lab astrophysics, etc…

- User facility open to frontier plasma science community
  - LBNL Workshop on science with BELLA-i (late fall)

- BELLA-i will help maintain and enhance US leadership in the world of ultrafast ultra-intense laser-driven science and applications
  - Vigorous competition overseas (e.g., 3 ELI facilities in Europe)
Extras
BELLA-i: Accelerator Science+Applications

Eric Esarey et al., LBNL
FES-HEP Briefing, DoE, May 21, 2015

Ion Acceleration

\[ E_{\text{ion}} = E_{\text{in}} \left( 1 - \frac{1}{4\gamma^2} \right) \]

Electron Acceleration

Relativistic Flying Mirrors

High Intensity Particle Physics
Novel mechanisms have been invented that promise to provide better beam quality

**Magnetic vortex acceleration**
- Requires
  - PW laser
  - High contrast
  - Near critical density targets

100's of MeV to GeV protons

The number of He$^3$ and He$^4$ ions per energy interval

![He ion density distribution](image)
High laser power at BELLA allows for the study of different mechanisms of ion acceleration.

**MVA**
- Laser: High Intensity
- Target: Near Critical Density slab
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**RPA**
- Laser: High Intensity
- Target: Thin solid density foils
- Ion Energy: hundreds of MeV
HHG accompanies ion acceleration in the laser irradiation of thin foil targets

HHG generation in plasma corona

Experiment:

PIC Simulations:

Theory:

HHG generation during the RPA of a thin foil


T. Zh. Esirkepov, et al., NIMA, 745, 150 (2014)

All major mechanical and electrical systems were installed and commissioned in 2012-2013.
e-Beam diagnostics include energy, transverse profile and charge transformers

- Single shot
- 30 MeV-11 GeV
- Two ICTs
- Phosphor screen
The proposed facility upgrade will be planned \textit{ab initio} as a user facility with community input

- LBNL runs multiple National and Local User Facilities (ALS, 88”, NCEM, Molecular Foundry)
- Experiments at BELLA will be proposal driven with PAC guidance (call once a year)
- During project design we will seek guidance through a Scientific Advisory Committee that will later transition into a Program Advisory Committee

88 Inch Cyclotron (DOE-NP, NRO, USAF)
Heavy Ion Facility
Nuclear Science
Applied Program

Advanced Light Source (DOE-BES)
3\textsuperscript{rd} Generation Light Source
35 Beamlines, Multidisciplinary program with 2000 users

Nanoscience Center – 7 Facilities
Access for proprietary customers