Plasma acceleration and high energy density science

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Close Collaborations with other
ATAP Programs & LBNL Divisions
BELLA Experimental Facilities: World-Leading Capabilities Driving Plasma Acceleration and HEDS

Existing and planned laser facilities in Building 71 at LBNL

BELLA-2\textsuperscript{nd} Beamline Staging (Project) 5+5 GeV staging

kBELLA (Initiative) kHz-kW LPA

BELLA-iP2 (Project) Ion acceleration, HEDS

BELLA-i beamline (Initiative)

Current PW: 10 GeV

100 TW MeV photons

TW Medical

100 TW FEL

Unique resource of and for the DOE and beyond
State of the art: 1 Hz at PW, 5 Hz at 100 TW
Ultraintense Lasers Enable Science and Applications: From the Frontiers of Fundamental Physics to Industry, Security and Medicine

HEP Future Particle Colliders
NP Nuclear Science

Extend energy frontier
Access exotic nuclear states

FES High Energy Density Science
NIH/NCI Oncology

Precision probes/pumps
New therapy sources

BES and Industry Coherent X-rays

Compact FELs
Molecular dynamics
Microelectronics

DoD, NNSA, Industry and Medical Sensing & X-rays

Precision
Mono-Energy
High res.
Remote sensing
Outline

- Plasma accelerators
- Advanced sources & high energy density science
- kHz precision frontier
BELLA Center is Focused on Executing the U.S. Advanced Accelerator Development Strategy

### 2016 LPA roadmap

<table>
<thead>
<tr>
<th>Year</th>
<th>Activity</th>
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</thead>
<tbody>
<tr>
<td>2015</td>
<td>Continuing Invention &amp; Discovery Phase</td>
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<tr>
<td>2020</td>
<td>Modeling and simulations with hi-fidelity, high speed codes</td>
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<tr>
<td>2025</td>
<td>10 GeV module</td>
</tr>
<tr>
<td>2030</td>
<td>Positrons</td>
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<tr>
<td>2035</td>
<td>BELLA Core program</td>
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<tr>
<td>2040</td>
<td>Development &amp; synergies</td>
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<td></td>
<td>Future lasers</td>
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- **Accelerators**
  - Prototype Phase
    - GeV linac – kHz rep rate
    - 50-100 GeV linac(s) – O(1-10kHz)
  - First applications (radiation sources)
  - Design of concepts for colliders
  - Collider conceptual design report (CDR)
  - Collider tech. design report (TDR)
- **Lasers**
  - 3 kW class
  - 30 kW class
  - 300 kW class

Updates in progress – Snowmass 2021
Precision Engineering of Relativistic Plasmas Enables High Performance

Resonant Excitation Results in Predicatable Structure
- Accurate scaling laws for charge, energy, laser requirements...

Example scalings
- $\lambda_p = \frac{2\pi c}{\omega_p} \sim n_e^{-1/2}$
- Gradient $\sim n_e^{1/2}$
- Energy $\sim 1/n_e$

Typical at $n_e \sim 10^{17}/\text{cm}^3$
- 100 µm
- 10 GV/m
- 10 GeV/stage in 10’s of cm

Scalings strongly validated: close integration of theory, experiment, and simulation

Allow design of accelerator systems
BELLA Center: Timeline of LPA Records

Since its beginnings in the mid 1990s, BELLA has been in the forefront of LPA performance, and recently continued its string of energy records by producing 8-GeV electron beams.

A second beamline dedicated to staging, and a second interaction point for studying ultrahigh-field interactions with tightly focused PW beams, are among the major near-term enhancements to our facilities.

2004: 10TW

2006: 40TW

2014: 300TW

2016: 40TW staging demo

2019: 1000TW & laser heater
The BELLA PW enables precision 1 Hz experiments

**BELLA PW laser performance**
- >40 J on target with a 1% level fluctuation
- <1.3 μrad pointing fluctuation
- Focus to 53 μm,
  - 75% energy in main structure,
  - <6% peak fluence fluctuation.
- Compressed to 33 fs,
  - >90% energy in main pulse
  - <5% peak power fluctuation.
- Peak intensity $1.7 \times 10^{19}$ [W/cm²]
  - <8% fluctuation.
- Contrast
  - 1 ns $>10^9$
  - 5 ps $>10^6$
Guiding of laser over many focal depths requires compensation for non-ideal laser mode

Laser close to a flat-top near field
16J, $n_e = 7.5 \times 10^{17}$

Density for guiding increased

Affects guiding and acceleration
Continuous Progress
Towards 10 GeV Collider-Class Per-Shot Stage

Efficient systems via control and development

- 2014: 4GeV. Using capillary waveguide
- 2017: 6GeV. Required a new beamline for hybrid waveguide (laser-heated capillary)
- 2018: 8GeV. Required optimization of the waveguide regime through theory & simulation

BELLA @ 0.85PW with laser-heated capillary

Towards efficient 10 GeV stages: shaped guides, controlled injection, structure and loading control…

Gonsalves et al., PRL (2019)
2nd Beamline Will Provide a Platform to Enable Key Elements of Advanced Accelerator R&D Roadmap

Staging

Injection & guiding

Positron generation & acceleration

2015  2020  2025  2030  2035  2040

Continuing Invention & Discovery Phase

Modeling and simulations with hi-fidelity, high speed codes

10 GeV module  Positrons  Multi-GeV staging

Design complete, installation in progress

Flexible Focusing and Controlled Injection
Key to Multi-GeV staging

Ionization injection at start of first stage
Controllable 4 GeV beam

- 2% N₂ (39 pC)
- 1% N₂ (23 pC)
- 0.8% N₂ (5 pC)

Extends 1.5 GeV experiment

Particle loss due to wake evolution, bunch size
Adjust with focal match: \( w_0 \sim 70 \) micron

Fraction charge @ LPA2 exit

Basis of near term multi-GeV staging experiment

Longer term: low emittance injector and matched guide for near 100% efficiency and 10 GeV

\*Gonsalves et al, POP (2020)
Ionization injection and other multi-beam experiments require precision control

Long wavelength drive laser/beam excites wake without injecting particles
  - High $a_0$, low $E$

Short wavelength injection laser injects particles without exciting wake
  - Low $a_0$, high $E$

Injection of sub-micron bunch with low transverse momentum enables nm-class emittance
  - Requires precision alignment $\leq \mu m$

Priority for active alignment, pilot beams and repetition rate to execute

L-L, Yu et al, PRL 2014
Outline

- Plasma accelerators
- Advanced sources & high energy density science
- kHz precision frontier
**Ion acceleration**

**In operation**, $2 \times 10^{19}$ W/cm$^2$, large laser spot, 50 μm, low divergence ion pulses with $\sim 10^{12}$ protons.

**Late 2021**, $> 10^{21}$ W/cm$^2$, small laser spot, $\sim 10$ μm, (ultra-)relativistic plasma science at 1 Hz, advanced ion acceleration mechanisms, ions to $> 100$ MeV, ...

LLNL collaborations/users including Tammy Ma, Scott Wilks, Derek Mariscal, Graeme Scott, Elizabeth Grace, Kelly Swanson, Raspberry Simpson (MIT)
BELLA PW Ion Acceleration and Transport Enabling Applications

Rep-rated experiments
- Tape-drive target and MCP-based Thomson Parabola Spectrometer
- Plasma lens focusing
- Thousands of shots
- Stable source enables applications

High rate precision ion science

Plasma lens: controlled focus

Materials

In-air setup:
1. scintillator
2. RCFs
3. radiation biology cell samples

High intensity laser beamline: new opportunities in discovery plasma science

Features
A. New target chamber for highest laser intensities $>10^{21} \text{W/cm}^2$
B. Double plasma mirror for temporal contrast enhancement of laser (ns-ps) $<10^{-14}$
C. Expansion space for diagnostic, probe laser, ion beamlines, betatron backlighter for WDM studies

Opportunities in
- **Fundamental Physics of Relativistic Plasmas**
  advanced ion acceleration, relativistic oscillating mirror, flying mirror
- **Relativistic Laboratory Astrophysics**
  plasma instabilities, bow waves, magnetized jets, antimatter plasma, collisionless shocks
Dual 100 TW laser systems drive photon sources and HEDS experiments

Precision MeV mono-energetic X-ray characterization

Flexible multi-beam HEDS

- 1 to 5 Hz, 2.4 J primary + 0.6 J 2nd beam, ≳40 fs, 800 nm
- Available now for high energy density science, ...

LLNL simulations with Dave Grote, Alex Friedman
Mono-energetic MeV photons by collision w/laser:
- Enable: precision measurements below μm & ps

New facility
Photon source operating

Reduce X-Ray & CT Dose 10x-100x and improve material separation 10x
- Application and user (LaserNetUS) experiments
- Next: 9 MeV photons, guiding, electron deceleration, energy spread at 10% level with path to below 1%

Strong mono-energetic photon source impact on nonproliferation Potential (unfunded) for HEDS, stockpile, defense/industry, medicine

**Energy selection:** enhances signal

- **Radiography:** maximize transmission and Z-contrast, reduce dose

<table>
<thead>
<tr>
<th>MPS dual energy ratio increases contrast</th>
<th>Energy spread at 20% level</th>
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<tr>
<td>MPS 9 &amp; 3MeV</td>
<td>Brem 9 &amp; 6 MeV</td>
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10x improved discrimination

Simulation: Marie-Anne Descalle, LLNL

fs emission: time resolution

**mrad divergence:** mitigates scatter

≥ micron emission spot: resolution


Enables precision measurements for nonproliferation, nuclear physics, medicine and industry

Cargo, single sided detection, treaty verification and safeguards cases detailed

Dose reduced 10x-100x with energy control + narrow divergence
Material discrimination improved 10x
Spatial and temporal resolution improved more than 100x (fs, micron)

LLNL collaboration with Harry Martz, Steven Glenn, Joseph Bendahan
LPA-FEL project: control phase-space to enable a LPA-based Free Electron Laser (a compact coherent X-ray source)

Transport studies in progress

LPA de-compression
- dE/E few-% to <1%

Strong-focusing undulator
- Preserve charge density

Phase 1: 100 MeV → 3eV FEL
- Phase 2: 300 MeV → 27eV FEL
  - Strong overlap with HEP
  - Novel phase-space diagnostics

Future: compact keV LPA FEL

Approaching required charge density on single 100 MeV shots

APS DPP 2020, talk by S. Barber (meetings.aps.org/Meeting/DPP20/Sessions/BO04.1)
LaserNetUS user access to PW and 100 TW systems

Goal: Bring together the high-intensity laser science community and enable a broad range of frontier scientific research.

- HEDS, light source, HEP oriented users
- Collaborative projects welcome
- Enables new science & facility capabilities

Recent proposal areas include:
- ion acceleration (upcoming LLNL run)
- plasma mirrors
- betatron sources, hydro and imaging
- NDE, material processing…

Synergistic BELLA R&D
- FLASH Radiation Biology with laser-plasma ion beams
- Quantum Information Science / Qbit & material synthesis
- COVID droplet microenvironments

www.LaserNetUS.org
Compact diagnostic enables single shot emittance measurements

Tight focusing (6cm APL) coupled to dipoles for high-resolution energy and emittance characterization

- 4-5 μm emittance from ionization injection, 0.25 PW in 1.3 e18 of 99% He / 1% N2
- Compact spectrometer (<60cm), range to above 10 GeV

Liquid crystal plasma mirror protects plasma lens (OSU collaboration)

- Sub-micron emittance degradation

Barber et al. APL 116, 234108 (2020)
HEDS probes: compact MeV penetrating sources + coherent keV sources + charged particles

Coherent precision

Penetrate dense cores, µm resolution

Field imaging

FEL: magnetic or plasma wake
Coherent XUV- SX
Thomson – counter prop. laser
e- bunch (coherent)
keV coherent x-rays
keV µm resolution
keV broad x-rays
Broadband, to 10’s of keV
Betatron – plasma wake focusing

Advanced imaging to enable precision HEDS, collaboration opportunity

Related: F. Albert et al LLNL
HEDS diagnostic opportunities / needs

- Narrow angle of emission implies longer stand off
- Need to know:
  - What is the desired probe energy, bandwidth
  - Photon # coupled to detector aperture at this energy
    Poisson Dynamic range? Target absorption dynamic range? Other?
  - Where is coherence needed? longitudinal, transverse?
  - When do we care about/need to block laser/electron effect on target?
- Diagnostic constraint: Narrow divergence 1-100 mrad (dep. on source & energy) implies longer source-to-target distance; therefore also longer target to detector
Outline

- Plasma accelerators
- Advanced sources & high energy density science
- kHz precision frontier
Science Need: kHz Key to Efficient, High Quality Accelerators & Ultrafast Science

Laser plasma accelerator potential shown
- Order of magnitude performance increase needed for HEP and applications
- Theory & simulation show attainable
Realizing potential requires precision

Increasing laser energy only does not enable applications – not efficient

Precision laser shaping and control required for quality and efficiency
- Laser pointing: from μrad to < 0.1 μrad
- Focal spot/wave front: now at fluctuation limit
- Near field: currently not well controlled
- Pulse shape, carrier envelope phase...

Ground & air motion fall off at O[100Hz]

Broad ultrafast science potential
- HEDS precision time resolved tomography over thousands of shots
- Attoscience, Molecular Dynamics, Sensing, Nuclear Science, Radiation biology
- Sources for Bioimaging, COVID, Microelectronics, HEP detectors,
- Applications limited by rate & performance
Realizing potential requires rate

Correction at kHz >10 fold - key to LPA performance

PW target chamber vibration in vacuum

95% below 200Hz → correctable at kHz
Laser Control and Stabilization for Precision LPA on Existing Lasers

kHz-mJ regen pilot beam to characterize 100TW system

- Wedged steering mirror: ‘copy’ of pulse
- Position and angle on target in both planes

Pilot well correlated to amplified pulse

- Diagnostics: non-perturbative at high-power
- Correction to be enabled at kHz – potential 10x improved pointing
- Path to correction of other parameters

Does not correct: pumping & beam size effects

Pilot well correlated to amplified beam
(oscillator-to-target beam-pilot overlap)

Fluctuation primarily < 100 Hz

FFT Position Hor. —, Vert. —

FFT Angle Hor. —, Vert. —

Isono et al. JOSAB (submitted), talk at APS DPP 2020 (https://meetings.aps.org/Meeting/DPP20/Session/TO03.4)
Ti:sapphire kHz Design Ready to Build

**Ti:sapphire – extend existing systems**

Near term 3J / GeV LPA available

Design detailed: Layout and > 200 line BOM

**Laser energy pump**
Diode pump lasers (Commercial)

Also: Colorado State, TRUMPF, MIT-LL

**Heat extraction**
Cryo cooling

**Compression**
Dielectric Gratings

Direct path to GeV kHz system for LPA studies.

LBNL - LLE - LLNL
MIT-LL and Colorado State discussions

Other technologies needed for high efficiency > few % and repetition rates beyond kHz class
Towards Application Luminosity Needs: Developing High Repetition Rate Lasers (Joint with BACI)

Fiber lasers enable: beyond kHz with high efficiency
- Critical for collider roadmap
- Combine ~100 fibers × Stack 100 pulses temporally for Joule energy

LBNL – U. M. – LLNL projects developing architecture
- Stewardship: Scalable diffractive combining – Combined 81 low energy beams
  - Coherent pulse stacking – Stacked 81 high energy pulses
- ECRP (Qiang Du): Controls for efficient combining & stacking
- New ECRP (Tong Zhou): Spectral combining for 30fs pulses & LPA demo

Near term path to hundreds of mJ, 10’s of fs systems
- Future 10 Joule class, 10’s of kHz collider drivers

Distributed Spectral Filtering preserves amplified bandwidth for short pulses
Laser Technology Path Established for Future High Efficiency

Fiber combination

R&D under accelerator stewardship program
- Technical roadmaps in progress for both technologies

Path in next 5 years for fiber and Tm:YLF
- 100’s of mJ, 100 fs class systems feasible
  - Build full Joule-class compressor & support systems to provide for future expansion
  - Laser development platform

Future path for fiber and Tm:YLF
- Highly efficient systems
  - 10’s of kHz at Joules of energy and 30-60fs

LLNL with LBNL discussion

 Courtesy: Tom Spinka, LLNL
kBELLA Initiative Under Development for kHz, Joule-class LPA

High priority in community and funding agency plans for precision LPA
- Ti:sapphire is ready to execute at GeV class in next few years
- Fiber & Tm:YLF offer path to future high efficiency, with lower energy in near term
- Facility supporting multiple lasers for immediate experiments and long term development
- Key step on collider roadmap and enables photon sources and precision HEDS
Summary

LPA performance advancing strongly
• 8 GeV record using laser-heated capillary

2nd Beamline will enable high quality LPA staging
• Platform for: controlled injection, laser produced guides, and positrons
• Flexible spot size will assist both staging and single stage campaigns

Photon sources, user experiments and ion acceleration reinforce program
• Common techniques with collider at accessible scale
• HEDS pumps and probes

Precision control of laser drivers is key to LPA advancement
• Path to efficient future kHz systems via fiber combination and other approaches
• kHz, Joule class is a key next step for control and applications

LBNL-LLNL collaboration opportunities ranging from simulations to ion acceleration to photon sources