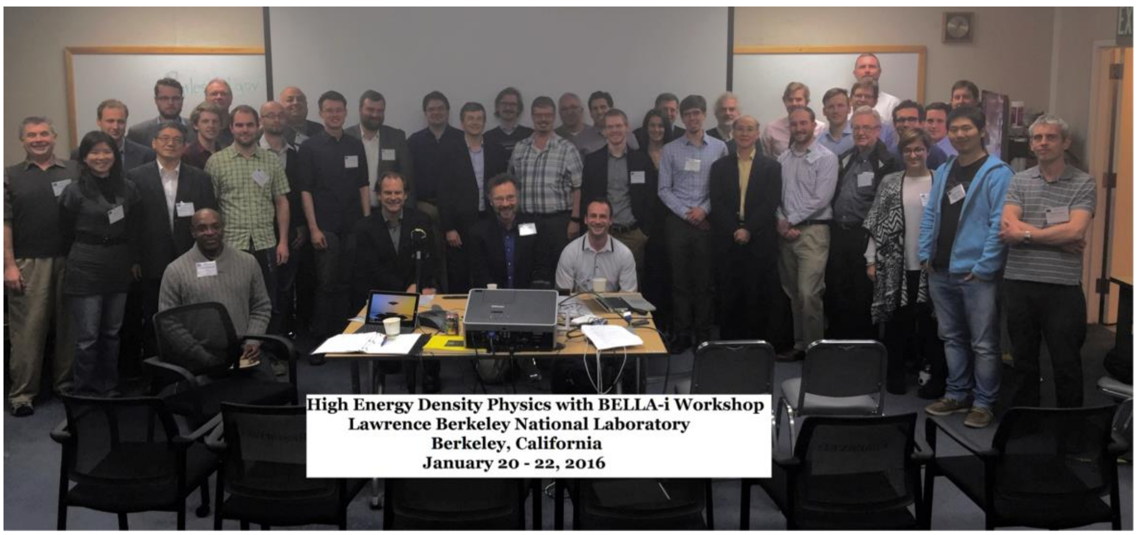
Workshop Report: High Energy Density Plasma Physics with BELLA-i

Wim Leemans, Thomas Schenkel, Eric Esarey, Sven Steinke, Qing Ji, Stepan Bulanov
Lawrence Berkeley National Laboratory, Berkeley, CA, Jan 20-22, 2016
https://conferences.lbl.gov/event/58

A workshop on High Energy Density Physics with BELLA-i was held at Berkeley Lab Jan 20 – 22, 2016. The workshop charge was to assess and discuss opportunities for high impact plasma science enabled by BELLA-i. BELLA-i is a proposed collaborative user facility at the Berkeley Lab Laser Accelerator center (BELLA), where the petawatt BELLA laser is currently used for laser plasma acceleration of electrons. At BELLA-i, the BELLA laser would also become available for research in high energy density plasma science. We envision three phases of development of BELLA-i.



The workshop was attended by over 60 scientists from US universities, national laboratories and from institutions overseas (see detailed attendance statistics below). Session were organized with talks along the following four topic areas:

topic area	**discussion leaders**
physics of laser-ion acceleration	B. M. Hegelich, S. Steinke
high harmonics and other secondary beam generation	F. Albert, J. van Tilborg
high field physics, onset of non-linear QED and nuclear-plasma physics	J. Wurtele, S. Bulanov
facilities (targetry, laser control, beam lines)	R. Shephard, Q. Ji

In the first phase of BELLA-I development, the existing long focal length beamline will be made available for high energy density plasma science experiments in an intensity regime up to a few times 10^{19} W/cm^2 with a full beam energy of 40 J in a relatively large laser focal spot. Higher intensities would be available via plasma focusing of the laser spot.

In the second phase of BELLA-i, high energy density plasma science experiments will be conducted with a short focal length beamline and intensities well above 10^{21} W/cm^2. Here, the

BELLA laser beam will be split into two beamlines to provide well synchronized pump and probe pulses. This second phase is particularly exciting because of the plans for experiments with two stages of laser-acceleration of electrons which provides many synergies for adding components that enable experiments in high energy density plasma science. The second beam also enables pump-probe experiments such as use of an LPA or radiation generated by it as the probe for an HED plasma. A single plasma mirror will also be available to improve contrast on the second beam line.

In the third phase, a new cave will be constructed with improved shielding and improved temporal laser intensity contrast (using dual plasma mirror technology) to enable interaction experiments with the main laser pulse at highest peak intensities. The experimental cave will house a target chamber for laser-ion acceleration and a beamline to transport laser accelerated ions for experiments in a benign radiation environment (see table 1 for details on the three phases of BELLA-i).

BELLA has established itself as a leading petawatt laser facility with excellent laser performance, and the opportunity to broaden the science focus of the BELLA petawatt laser into high energy density plasma physics was met with enthusiastic support by the attendees. Concrete suggestions for high impact phase 1 experiments quickly emerged and were discussed between attendees and BELLA center staff. Examples include experiments on plasma-based optics to increase the laser peak intensity and temporal intensity contrast such as plasma lenses and plasma mirrors and studies of their effect on laser-ion acceleration, as well as the generation of betatron radiation at high laser pulse energies of 40 J and measurements of laser energy partitioning into radiation, electrons and ions.

BELLA-i	phase 1	phase 2	phase 3
peak intensity (W/cm^2)	~2×10^{19}	3×10^{21}	$\geq 3 \times 10^{21}$
pulse length	30 fs	30 fs	30 fs
peak pulse energy	40 J	40 J	40 J
laser spot size	55 µm	5 µm	≤ 5 µm
peak repetition rate	1 Hz*	1 Hz*	1 Hz
contrast (ns)	10^{-10}	10^{-10}	$>10^{-14}$
diagnostics (details to be determined)	• optical and XUV spectrometers • ion and electron spectrometers • …	• optical pump- probe • betatron x-rays • MeV protons • …	• same as 2 • beamline for experiments with laser accelerated ions • …
1st access (estimates)	2017-2018	2018-2019	2019-2020

Table 1: Summary of BELLA-i parameter for the envisioned three phases of development.

The discussions highlighted the unique competitive advantages of the BELLA petawatt laser, which has unrivaled performance metrics (stability, wave front control, and especially the repetition rate of 1 Hz). Conducting high energy density plasma science experiments with the BELLA laser promises to have disruptive impact in high energy density plasma science by propelling a transition from today's single shot experiments in campaigns of a few tens of shots to a new era of "science with error bars" in high energy density plasma science where repetition rates up to 1 Hz will enable 100 to 1000 times more shots than is currently possible at existing PW laser facilities. Required targetry and diagnostics were discussed at the workshop and are rapidly developing to be available for high shot rate campaigns.

The unique combination of high repetition rate and exquisite laser quality combined with high laser contrast and ultra-high intensities well above 10^{21} W/cm^2 (and quite possibly above 10^{22} W/cm^2 with low f-number optics in phase 3), together with the ability to utilize two counter- or co-propagating laser beams (in phase 2) promise a series of high impact breakthroughs at the frontiers of relativistic plasma science. Fields include nonlinear QED, relativistic flying mirrors, laser ion acceleration, astrophysical and nuclear science.

Relativistic plasma science in the high field regime where non-linear QED effects begin to dominate the plasma dynamics has important consequences for our fundamental understanding of laser-matter interactions. These effects are part of a new emerging branch of physics at the border of laser-plasma interaction studies and particle physics, which occupies a significant region in the Standard Model parameter space but is largely unexplored to date, both theoretically and experimentally. The study of laser-matter interactions in the regime of high intensity offers a unique opportunity for the controlled exploration of nonperturbative and nonlinear phenomena in the multiphoton and tunneling regimes of relativistic plasmas.

The basic plasma physics of relativistic flying mirrors is one showcase example where high laser quality, high repetition rate and ultra-high fields can bring about a demonstration of a physics effect that was predicted by Einstein in 1905. Advances in relativistic engineering of flying mirrors could lead to dramatic shortening of the wavelength and focusing of a second laser beam, possibly leading to record breaking laser intensities where the basic plasma physics of dense jets of electron-positron pairs emerges and were we will be able to create in the laboratory scaled conditions similar to those found in relativistic astrophysical plasma environments.

Laser-ion acceleration was widely discussed with invited talks from several leading research groups. This is a topic of great fundamental importance with rapidly emerging application areas in medicine, radiation effects testing of electronics and materials science. First experiments on laser-ion acceleration have been reported over 15 years ago. With the high laser quality and ultra-high fields at BELLA-i, new regimes with potentially much increased ion energies (>100 MeV/u) are predicted by simulations. BELLA-i experiments also offer the potential to unify and advance currently proposed scaling laws of ion acceleration because pulse durations ranging from 30 fs to 400fs would become accessible for the first time with a laser of this class. BELLA-i will thus play a decisive role in determining the laser technology needed to reach ion energies required for, e.g. medical applications with ion energies >250 MeV. The projected ultrahigh temporal contrast reduces the duration of the laser-target interaction to timescales of order hundreds of fs instead of ~ns and hence significantly shortens the required computation time of full-scale modelling. This is exciting because it will allow rapid iteration of experiments guided by detailed simulations. The intriguing prospect is then to accomplish with ions what has been achieved in recent years with laser-accelerated electrons, making laser-ion acceleration a highly promising area of high energy density plasma science at BELLA-i.

The unique context of excellence in beam physics and (superconducting) magnet technology at Berkeley Lab makes the exciting prospect of capturing laser-accelerated ions into an ion beam line accessible. Here, intense ion pulses would be transported into an area with a benign radiation environment, meters away from the primary laser target. Delicate samples, including space electronics and biological materials can then be excited and probed. Basic science experiments, e. g. in the area of warm dense matter for planetary science, can be conducted with isochoric heating of large sample volumes by intense ion pulses. These basic plasma science studies could also lay the foundation of a new class of hadron therapy technologies and novel tools for active nuclear interrogation of materials.

Discovery plasma science at BELLA-i will connect to several astrophysical and planetary science areas, from relativistic plasmas and pair production, to the warm dense matter physics of planetary interiors. Recent theoretical analysis predicts that the dense plasma environments formed at BELLA-i will significantly modify the rate of specific nuclear processes, e. g. of reaction rates critical for our understanding of nucleosynthesis in dense stellar plasmas. Controlled plasma conditions might also enable access to long lived nuclear states which challenge our understanding of basic nuclear physics effects and might lay the foundation of future applications in nuclear photonics.

Vibrant discussions highlighted the global context of fierce competition with several large laser facilities currently being planned or under construction in Europe and Asia. It was pointed out by several attendees that a unique opportunity for BELLA-i in the next five years is posed by the fact that BELLA is already up and running at the highest level of laser excellence.

Attendees expressed interest in proposing first experiments that are enabled by the unique large spot size currently available at BELLA. The planning of these experiments will help define the future facility needs and help refine BELLA laser capabilities such as pulse contrast and laser diagnostics. A relatively modest and timely investment can quickly push the doors wide open for a wealth of cutting edge discovery plasma science at the BELLA-i collaborative user facility. Subsequent workshops are being planned to develop details for first experiments as well as the overall facility on diagnostics (particle and laser, including probe beams), targets and target chambers. Letters of support are being compiled and will be provided to DOE under separate cover.

Metrics of the BELLA-i workshop (more info under: **https://conferences.lbl.gov/event/58/)**

- 63 registrants
  - US: 44
  - Non-US: 19
- US National Laboratories: 30
  - LBNL: 17
  - LLNL: 8
  - LANL: 1
  - SLAC: 2
  - NRL: 2
- US Universities: 11
  - Ohio State University: 2
  - Rice University: 1
  - Stanford: 1
  - UC Berkeley: 2
  - UC San Diego: 1
  - U Michigan:1
  - U Rochester, LLE: 2
  - U Texas, Austin: 1
- US private companies: 3
  - RadiaSoft LLC: 2
  - Polymath research Inc.: 1
- Non-US: 19
  - Chalmers U, Sweden: 6
  - DESY, Germany: 1
  - ELI Beamlines: 1
  - HZDR, Dresden, Germany: 1
  - INFN, Catania, Italy: 1
  - Instituto Superior Técnico, Portugal: 1
  - LMU, Munich, Germany: 1
  - Max-Planck Heidelberg, Germany: 2
  - Peking U, China: 1
  - Queens's U, Belfast, UK: 1
  - Rutherford Appleton, UK: 1
  - TU Darmstadt, Germany: 1
  - U Electro-Com., Tokyo, Japan: 1