PROCEEDINGS OF SPIE

Advances in X-ray Free-Electron Lasers: Radiation Schemes, X-ray Optics, and Instrumentation

Thomas Tschentscher
Daniele Cocco
Editors

20–21 April 2011
Prague, Czech Republic

Sponsored and Published by
SPIE

Cooperating Organisations
ELI Beamlines
HiPER

Volume 8078

Proceedings of SPIE, 0277-786X, v. 8078

Please use the following format to cite material from this book:
Author(s), "Title of Paper," in *Advances in X-ray Free-Electron Lasers: Radiation Schemes, X-ray Optics, and Instrumentation*, edited by Thomas Tschentscher, Daniele Cocco, Proceedings of SPIE Vol. 8078 (SPIE, Bellingham, WA, 2011) Article CID Number.

ISSN 0277-786X
ISBN 9780819486684

Published by
SPIE
P.O. Box 10, Bellingham, Washington 98227-0010 USA
Telephone +1 360 676 3290 (Pacific Time) · Fax +1 360 647 1445
SPIE.org

Printed in the United States of America.

Publication of record for individual papers is online in the SPIE Digital Library.

SPIE Digital Library

SPIEDigitalLibrary.org

Paper Numbering: Proceedings of SPIE follow an e-First publication model, with papers published first online and then in print and on CD-ROM. Papers are published as they are submitted and meet publication criteria. A unique, consistent, permanent citation identifier (CID) number is assigned to each article at the time of the first publication. Utilization of CIDs allows articles to be fully citable as soon as they are published online, and connects the same identifier to all online, print, and electronic versions of the publication. SPIE uses a six-digit CID article numbering system in which:

- The first four digits correspond to the SPIE volume number.
- The last two digits indicate publication order within the volume using a Base 36 numbering system employing both numerals and letters. These two-number sets start with 00, 01, 02, 03, 04, 05, 06, 07, 08, 09, 0A, 0B … 0Z, followed by 10-1Z, 20-2Z, etc.

The CID number appears on each page of the manuscript. The complete citation is used on the first page, and an abbreviated version on subsequent pages. Numbers in the index correspond to the last two digits of the six-digit CID number.

Contents

STATUS OF OPERATIONAL AND PLANNED FEL FACILITIES

SCIENTIFIC APPLICATIONS AND THEIR INSTRUMENTATION REQUIREMENTS II

OPTICS AND BEAM TRANSPORT PERFORMANCE

DIAGNOSTICS OF FEL RADIATION

FEL INSTRUMENTATION AND SAMPLE RELATED ISSUES

ADVANCED FEL RADIATION SCHEMES

POSTER SESSION

Conference Committee

Symposium Chairs

Miroslav Hrabovský, Palacký University Olomouc (Czech Republic)
Wolfgang Sandner, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany) and Laserlab Europe
Bahaa Saleh, CREOL, The College of Optics and Photonics, University of Central Florida (United States)
Jan Řídký, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

Symposium Honorary Chair

Jan Peřina, Sr., Palacký University Olomouc (Czech Republic)

Conference Chairs

Thomas Tschentscher, European XFEL GmbH (Germany)
Daniele Cocco, Sincrotrone Trieste S.C.p.A. (Italy)

Program Committee

Fred Bijkerk, FOM-Institute for Plasma Physics Rijnhuizen (Netherlands)
Roberto Cimino, Istituto Nazionale di Fisica Nucleare (Italy)
Christian David, Paul Scherrer Institut (Switzerland)
Klaus Mann, Laser-Laboratory Göttingen e.V. (Germany)
Aymeric Robert, SLAC National Accelerator Laboratory (United States)
Kai I. Tiedtke, Deutsches Elektronen-Synchrotron (Germany)
Makina Yabashi, SPring-8 (Japan)
Philippe Zeitoun, ENSTA-LOA (France)

Session Chairs

1 Status of Operational and Planned FEL Facilities
Roberto Cimino, Istituto Nazionale di Fisica Nucleare (Italy)

2 Scientific Applications and their Instrumentation Requirements I
Robert Aymeric, SLAC National Accelerator Laboratory (United States)

3 Scientific Applications and their Instrumentation Requirements II
Robert Aymeric, SLAC National Accelerator Laboratory (United States)

4 Optics and Beam Transport Performance
Klaus Mann, Laser-Laboratory Göttingen e.V. (Germany)

5 Diagnostics of FEL Radiation
Kai Tiedtke, Deutsches Elektronen-Synchrotron (Germany)

6 FEL Instrumentation and Sample Related Issues
Makina Yabashi, SPring-8 (Japan)

7 Advanced FEL Radiation Schemes
Philippe Zeitoun, Ecole Nationale Supérieure de Techniques Avancées (France)

Introduction

Free-electron lasers (FEL) facilities based on low emittance electron accelerators and generating highly brilliant radiation in the short-wavelength regime from the vacuum-ultraviolet to hard x-ray have become reality. The scientific exploitation of these new sources has started and with new facilities the experimental program flourishes at present. Following the initial phase of demonstrating the feasibility of short-wavelength FEL radiation, the scientific experiments define better and more precise the requirements to FEL beam parameters and thereby guide the development of new, advanced schemes for FEL operation, for x-ray beam transport and shaping, and for x-ray instrumentation in general. Since FELs operate distinctly different to both high power optical laser and synchrotron radiation facilities, there exists a strong demand for new experimental techniques and for new instrumentation. New radiation schemes will push the FEL performance even further.

With operating electron accelerator-based FELs and providing extremely brilliant x-ray radiation now routinely the effort has to be augmented in developing the necessary x-ray instrumentation to perform the high-level applications the scientific communities strive for. In several areas there exist still challenges to be overcome by new ideas and new concepts for realization. This conference therefore aimed at outlining current and future advances in the field of x-ray instrumentation for FEL science. In presenting highlight scientific applications of recent years and their instrumentation requirements the motivation was provided for the topics new FEL sources, optics for and diagnostics of FEL radiation, sample schemes and detectors, and advanced FEL schemes that were addressed in the various sessions.

The realization of FELs for x-ray radiation took a big leap in the 1990's when new concepts for single-pass and high gain were introduced [1,2] and electron accelerators with the required small emittance became available. Motivated by the outstanding performances of x-ray FEL radiation a world-wide activity started to develop concepts for facilities delivering FEL radiation for scientific experiments. The FEL simulations indicated that sub-femtosecond pulse duration, spatial coherence, and extreme peak power would be provided. The predicted increase in peak brilliance was very high and was considered to enable new x-ray techniques and the access to new x-ray phenomena and new scientific applications. The success of the first test machines delivering radiation in the visible and VUV wavelength regime [3,4] allowed indeed the observation of new phenomena in the interaction of intense FEL radiation pulses with matter [5].

These first results sparked an even stronger interest in scientific applications of FEL radiation and prepared the ground for approval of a number of FEL projects for VUV to x-ray radiation around the globe. The first user facility entering into operation was the Free-Electron-LASer in Hamburg (FLASH) at Deutsches Elektronen-Synchrotron in Hamburg [6,7]. This facility initially operated at electron energies of 1 GeV providing photon energies up to 200 eV and its scientific user program commenced in 2005. The operation of FLASH showed that much shorter x-ray pulse duration than predicted could be provided, thus emphasizing the capability to study ultrafast dynamics. Further FEL facilities for the visible to XUV regimes came into operation in Japan (Small Compact SASE Source (SCSS) at Spring-8) and Italy (SPARC at Frascati). The first facility to reach the hard x-ray regime was the Linac Coherent Light Source (LCLS) at Stanford Linear Accelerator Center in Menlo Park [8] were user experiments started in fall 2009 for soft x-ray and in fall 2010 for hard x-ray radiation. At the end of 2010 the FERMI@Elettra FEL in Trieste reported first XUV light generated by using high-gain harmonic generation (HGHG) seeding and in spring 2011 the Spring-8 Angstrom Compact Free Electron Laser (SACLA) at Spring-8 reported first spontaneous radiation. Both results were presented at this conference. In parallel several other projects progress in their design and construction phases. FLASH, being one of the first FEL facilities, already underwent an upgrade program towards higher electron energy providing higher photon energies and a second FEL undulator and photon beamline will be constructed until 2014.

While the first user facilities make use of the self-amplified spontaneous emission (SASE) scheme of FEL generation [9] the development of more advanced FEL schemes has been progressing. At SCSS and SPARC experiments using optical laser radiation to directly seed the FEL process have been carried out [10]. FERMI is employing seeding and HGHG schemes for its user operation mode [11]. These advanced FEL schemes provide a lot of promise towards higher performance of FEL radiation. In particular the spectral purity and the longitudinal coherence of the seeded FEL radiation can improve significantly. A further aspect is improving the stochastical radiation properties inherent to the SASE mode of FEL operation. Current seeding schemes are most promising for the visible to XUV regime and their extension into the hard x-ray regime requires further investigation. Two promising concepts to reach the x-ray regime were discussed at this conference.

Scientific experiments using FEL radiation have to consider the particular aspects of these sources. Many experiments take single-shot data while beam properties fluctuate strongly. This requires both high repetition rate data taking and photon diagnostics operating at the x-ray pulse frequency. The high repetition rate poses a particular challenge for the read-out frequency of two-dimensional area detectors. With these requirements FELs differ from high power laser facilities operating at much lower frequency and from synchrotron radiation facilities where data are typically integrated over many x-ray pulses. In addition, accurate characterizations of the temporal and coherence properties of FEL radiation are completely new fields of hard x-ray instrumentation for which further research and development are needed.

The program of this conference encompassed the major areas of FEL instrumentation. The status of development of FEL sources was presented for nearly all projects pursued in the moment. The first beams at FERMI and SACLA being particular highlights. The presentation of a wide range of scientific experiments carried out at operating facilities allowed to review the requirements of FEL experiments to x-ray instrumentation and to point out the future needs. A first instrumentation area to be discussed was the x-ray optics for transport and for spatial, spectral and temporal shaping of the FEL radiation pulse delivered to the sample. In this area special emphasis is put on the preservation of the extreme peak brilliance and the high power of the FEL beam being reflected by the optical elements, and on new methods to temporally shape the x-ray pulse. The characterization of the FEL radiation was a further topic. Here, special attention was devoted to the characterization of temporal, wavefront and coherence properties. The discussion of sample environments and of x-ray area detector developments focused in particular on techniques enabling very high repetition rates of order MHz which are provided by super-conducting electron accelerators like available at FLASH and at European XFEL. The final session concentrated on new and advanced schemes for seeding FEL radiation with an emphasis to be suitable for the hard x-ray regime.

The success of this conference will have to be evaluated by its contribution to broaden this field and to attract new researchers and scientific groups to this field. The initial step towards new science using FELs has been achieved very successfully, now the next steps need to be made.

References

1. A.M. Kondratenko, E.L. Saldin, "Generation of Coherent Radiation by a Relativistic Electron Beam in an Undulator", Part. Accelerators 10, 207 (1980).
2. R. Bonifacio, C. Pellegrini, L.M. Narducci, "Collective Instabilities and High-Gain Regime in a Free-Electron Laser", Opt. Commun. 50, 373 (1984).
3. S.V. Milton et al., "First lasing and operation of an angstrom-wavelength free-electron laser", Science 292, 2037 (2001).
4. V. Ayvazyan et al., "Generation of GW Radiation Pulses from a VUV Free-Electron Laser Operating in the Femtosecond Regime", Phys. Rev Lett. 88, 104802 (2002).
5. H. Wabnitz et al., „Multiple ionization of atom clusters by intense soft X-rays from a free-electron laser“, Nature 420, 482 (2002).
6. V. Ayvazyan et. al., "First operation of a free-electron laser generating GW power radiation at 32 nm wavelength," *Eur. J. Phys.* D37, 297 (2006).
7. W. Ackermann et al., "Operation of a free-electron laser from the extreme ultraviolet to the water window", Nature Photonics 1, 336 (2007).
8. P. Emma et al., "First lasing and operation of an angstrom-wavelength free-electron laser", Nature Photonics 4, 641 (2010).
9. E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, *The Physics of Free Electron Lasers*, Springer, Berlin 1999.

10. G. Lambert et al., "Injection of harmonics generated in gas in a free-electron laser providing intense and coherent extreme-ultraviolet light", Nature Physics 4, 296 (2008).
11. E. Allaria et al., The FERMI@Elettra free-electron-laser source for coherent x-ray physics: photon properties, beam transport system and applications, New Journal of Physics 12, (2010)

Thomas Tschentscher
Daniele Cocco