
# Report of the High-Energy X-ray FELs Workshop

## Exploring the New Frontier of High-Energy and High-Flux X-ray Free-Electron Lasers

**July 9-11, 2019**

**Hilton Santa Fe Buffalo Thunder Resort**

**Santa Fe, New Mexico**

## Executive Summary

This report covers the findings of the High-Energy X-ray FELs Workshop that was held on July 9-11, 2019 at the Hilton Santa Fe Buffalo Thunder Resort. A total of thirty-five free-electron laser, accelerator and X-ray optics experts gathered to discuss the latest technological advances in electron beams, X-ray optics and novel FEL interaction mechanisms that will enable the design of a high-energy X-ray free-electron laser (XFEL) in the 40 – 100 keV energy range. This energy range is of interest to the Los Alamos National Laboratory because it is applicable to the characterization of high-Z materials thanks to its penetrating power.

The first challenge of an XFEL generating X-rays in the 40 – 100 keV energy range is how to generate and accelerate electron beams with sufficiently high electron beam energy, beam brightness, i.e., high bunch charge with low emittance in both transverse directions, high peak current and low energy spread. The second challenge is how to enhance the FEL interaction to generate a large number of high-energy X-ray photons in each electron bunch, and how to produce a macropulse with multiple X-ray pulses for dynamic materials studies. The third challenge is to identify advanced technologies in undulators and novel FEL interaction such as harmonic lasing to support FEL operation at high photon energies.

To meet these challenges, we organized the workshop into three working groups (WG). The first WG was focused on the generation, acceleration and manipulation of bright electron beams. The second WG was focused on new FEL interaction and advanced techniques that would lead to a high-fluxed high-photon-energy X-ray FEL. The third WG was focused on the advanced undulator technologies such as superconducting undulator and harmonic lasing.

Overall the Workshop was an excellent forum to share and discuss many ideas on how to advance the electron beam injectors and accelerators, X-ray optics, FEL interaction and new undulators to the next levels in order to meet the requirement of a 40 – 100 keV XFEL. Thanks to the small-group discussion and the cross fertilization among the three WGs, we have come up with a number of concepts that enable the design of a MaRIE-class XFEL. A detailed summary for each of the three WGs is presented in this report. The following is a highlight of the main findings of this Workshop:

- The general consensus is that a MaRIE class XFEL can probably be built using superconducting RF accelerator structures similar to that of the EuXFEL in the near term, perhaps with a different buch compression technique such as eSASE. In the medium and far terms, alternative accelerator structures such as the high-gradient room-temperature copper, cryo-cooled Cu structures, etc. should be investigated as a possible cost-effective accelerator for the MaRIE-class XFEL.
- Novel FEL interactions, specifically those involving an optical cavity such as RAFEL and XFELO, will be tested in the next few years and could potentially be a game-changer for the generation of high-fluxed, high-energy coherent X-rays.
- Harmonic lasing based on existing undulator technologies to support a 100 keV XFEL is being considered for the EuXFEL. Superconducting undulators are still being developed at ANL and they could be used as short-period undulators for future high-energy XFELs.

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## 1. Workshop Purpose

The purpose of the conference is to provide subject matter experts an opportunity to learn from one another and to discuss the latest technological advances in electron beams, X-ray optics and novel FEL interaction mechanisms that will enable the design of a high-energy X-ray free-electron laser (XFEL) in the energy range 40 – 100 keV. This X-ray energy range is important for the future MaRIE XFEL to characterize the properties of high-Z materials in extreme environments. The main challenge is how to obtain a train of multiple sub-picosecond X-ray pulses, with each pulse containing a large number of penetrating high-energy X-ray photons, for dynamic materials science studies. Our goal for this workshop is to explore new concepts and advanced techniques that would enable the design of a high-flux, high-photon-energy X-ray FEL.

## 2. Workshop Agenda and Plenary Talks

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***Tuesday July 9, 2019 Plenary Talks***

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|---|---|
| 8:30 - 9:00 AM | C. Barnes (LANL), "The Capability Gap for Dynamic Mesoscale Materials Science, and the Need for Energy, Brightness, and Ever-Better Photon Qualities" |
| 9:00 - 9:30 AM | K. Evans-Lutterodt (BNL), "High-energy X-ray Optics" |
| 9:30 - 10:00 AM | W. Graves (ASU), "Compact X-ray FEL with Patterned Electron Beams" |

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| 10:00 - 10:30 AM | Break |
| 10:30 - 11:00 AM | K.J. Kim (ANL), “XFELO” |
| 11:00 - 11:30 AM | G. Marcus (SLAC), “Regenerative Amplifier FEL for the LCLS-II” |

***Wednesday July 10, 2019 Plenary Talks***

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|---|---|
| 8:30 - 9:00 AM | T. Raubenheimer (SLAC), “The LCLS-II-HE X-ray FEL at SLAC” |
| 9:00 - 9:30 AM | Q. Marksteiner (LANL), “eSASE as Bright Beam Compression for XFEL” |
| 9:30 - 10:00 AM | Y. Li (EuXFEL), “Towards 100 keV lasing of the European XFEL” |
| 10:00 - 10:30 AM | Break |
| 10:30 - 11:00 AM | Y. Ivanyushenkov (ANL), “Superconducting Undulator Work at Argonne” |
| 11:00 - 11:30 AM | J. Rosenzweig, “Ultra-compact XFELs using very high gradient cryogenic RF techniques and advanced undulators” |

## 3. Working Groups and Break-out Talks

**Bright Beam Generation, Acceleration and Manipulation WG**

Chairs: Steven Russell and Kip Bishofberger

***Tuesday July 9, 2019***

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|---|---|
| 1:30 - 2:00 PM | D. Li (LBNL), “The LCLS-II-HE X-ray FEL at SLAC” |
| 2:00 - 2:30 PM | N. Moody (LANL), “Photocathode Options for High-Energy X-ray FEL” |
| 2:30 - 3:00 PM | Break |
| 3:00 - 3:30 PM | R. Robles (UCLA), “Bunch Compression Study for a Compact X-ray Free Electron Laser” |
| 3:30 – 4:00 PM | K. Bishofberger (LANL), “Long-range Wakefields in Superconducting Cavities” |
| 4:00 – 4:30 PM | A. Scheinker (LANL), “Demonstration of Adaptive Machine Learning Methods for Beam Phase Space Control and Maximization of FEL Pulse Energy at the EuXFEL and the LCLS.” |

**Novel XFEL Physics and X-ray Optical Configurations WG**

Chairs: William Colson and Tor Raubenheimer

***Tuesday July 9, 2019***

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|---|---|
| 1:30 - 2:00 PM | A. Halavanau (SLAC), “High Power and Brightness Double Bunch LCLS-II” |

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| 2:00 - 2:30 PM | S. Benson (JLab), "ERL-based X-ray FELs" |
| 2:30 - 3:00 PM | Break |
| 3:00 - 3:30 PM | Yu. Shvyd'ko (ANL), "X-ray Optics for Cavity-based XFELs" |
| 3:30 – 4:00 PM | H. Freund (CCR), "An X-ray Regenerative Amplifier Free-Electron Laser using Diamond Pinhole Mirror" |
| 4:00 – 4:30 PM | D. Nguyen (LANL), "Regenerative Amplifier FEL with a Thin Diamond as the Power Outcoupler." |

***Wednesday July 10, 2019***

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|---|---|
| 1:30 - 2:00 PM | Z. Zhang (SLAC), "Attosecond X-ray Pulse Generation based on Self-Modulation in a Wiggler" |
| 2:00 - 2:30 PM | H. Freund (CCR), "Studies of a Terawatt X-ray Free-Electron Laser" |
| 2:30 - 3:00 PM | Break |
| 3:00 - 3:30 PM | V. Yakimenko (SLAC), "Gamma-ray Source based on Current Filamentation Instability" |
| 3:30 – 4:00 PM | R. Ryne (LBNL), "High Resolution Simulation of Classical Undulator Radiation Using the LW3D Code." |

**Advanced Undulator Technologies WG**

Chairs: Joachim Pflueger and Dinh Nguyen

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|---|---|
| 1:30 - 2:00 PM | Y. Li (EuXFEL), "Undulator Parameter and Technology Studies for the Ultra-High Photon Energy XFELs" |
| 2:00 - 2:30 PM | J. Pflueger (EuXFEL), "The European XFEL Undulator Systems - a Lead for MaRIE" |
| 2:30 - 3:00 PM | Break |
| 3:00 - 3:30 PM | T. Tanabe (BNL), "Comparison of CPMU and SCU as High-energy and High-flux X-ray Free-Electron Laser's Sources" |
| 3:30 – 4:00 PM | H. Nuhn (SLAC), "LCLS-II Undulator System Tolerance Budget Analysis" |

# 4. Bright Beam Generation, Acceleration and Manipulation WG Summary

Six presentations were relevant for this session: five talks in the breakout session and one plenary.

1) Derun Li, LBNL (breakout talk): Progress on Normal Conducting CW APEX2 Electron Gun Design

2) Nathan Moody, LANL (breakout talk): Photocathode Options for High-Energy X-ray FEL

3) River Robles, UCLA (breakout talk): Bunch Compression Study for a Compact X-ray Free Electron Laser

4) Kip Bishofberger, LANL (breakout talk): Long-range Wakefields in Superconducting Cavities

5) Alex Scheinker, LANL (breakout talk): Demonstration of Adaptive Machine Learning Methods for Beam Phase Space Control and Maximization of FEL Pulse Energy at the EuXFEL and the LCLS

6) James Rosenzweig, UCLA (plenary talk): Ultra-compact XFELs using very high gradient cryogenic RF techniques and advanced undulators

## Derun Li: Progress on Normal Conducting CW APEX2 Electron Gun Design

In this talk, Derun Li presented the results of beam simulations and RF design modeling for the APEX2 photoinjector. APEX2 is based on the original APEX (Advance Photoinjector Experiment) photoinjector, which is the baseline design for the LCLC II XFEL. Using large scale global genetic algorithm optimization, LBNL improved the APEX2 RF performance beyond what has been demonstrated by APEX:

RF performance -

1) 162.5 MHz RF frequency
2) 90 kW of CW input RF power (same as APEX)
3) 30 MV/m gradient at photocathode surface (compared to 19 MV/m for APEX)

Beam performance –

1) 100 pC bunch charge
2) 12 A peak current at gun output (similar to APEX)
3) 0.1 micron emittance

Furthermore, preliminary analysis of an APEX2 geometry scaled to 217 MHz shows even better RF performance. However, the beam dynamics analysis is still pending.

LBNL has demonstrated that we can fabricate very bright, normal conducting CW photoinjector sources. This should be compared to SC photoinjectors, which are still aspirational for practical accelerator facilities.

## Nathan Moody: Photocathode Options for High-Energy X-ray FEL

In this talk, Nathan Moody presented work conducted at LANL to improve the design and fabrication of photocathodes, with an emphasis on the application of this work to XFELs. Over the last several years, LANL has brought modern materials science techniques and approaches to photocathode development:

1) Predictive theory and validation.
2) Nano-material synthesis and fabrication.
3) In-situ surface science characterization.
4) Measurement and correlation of beam properties.

These techniques, although not necessarily new to materials science, are new for this application. This opens up opportunities to improve photocathode performance across what have been in the past mutually exclusive metrics. For example, improved QE while also maintaining photocathode lifetime.

## River Robles: Bunch Compression Study for a Compact X-ray Free Electron Laser

One of the great challenges in XFEL design is generating the very high peak currents (many kAs) necessary for efficient lasing. Our best electron sources typically can only produce beams with 10s, to maybe 100s, of amps of peak current. This necessitates beam compression using correlated energy chirps together with magnetic chicanes, or similar techniques. However, longitudinal compression in magnetic fields is a notoriously difficult process when one also needs to preserve beam quality. In this talk, River Robles presented recent numerical analysis of a compression scheme using the eSASE interaction. He begins with a very bright electron source (~50 nm emittance), bunches the initial beam to 400 A using standard techniques, and then performs a final compression using eSASE to generate a chain of 4kA micro-bunches. Initial results are promising, showing emittance growth as low as 200 nm.

## Kip Bishofberger: Long-range Wakefields in Superconducting Cavities

Kip Bishofberger gave a talk summarizing current results from a long-range wakefield study done at the FAST facility at Fermilab. Wakefields in the two, TESLA type cryomodules at FAST were studied using chains of beam bunches. By deliberately steering the beam off axis, higher order modes (HOMs) could be excited and the effects observed by measuring how the beam was steered using downstream BPMS and by measuring the emittance. Kip presented data and the analysis that has been done so far. The goal of this experiment is to validate wakefield codes and predictions.

## Alex Scheinker: Demonstration of Adaptive Machine Learning Methods for Beam Phase Control and Maximization of FEL Pulse Energy at the EuXFEL and the LCLS

Alex Scheinker reported recent results that combined machine learning (ML) for rapid global optimization and model independent extremum seeking (ES) to automate tuning of XFEL parameters at the EuXFEL and LCLS. Examples were shown where ES by itself was employed to tune up EuXFEL and LCLS to maximize output SASE FEL power and to tune the machine for a particular longitudinal phase space distribution. However, ES is a local optimization method, and so the hope is to combine it with ML for global optimization.

Since accelerator facilities are generally very “noisy”, one cannot employ ML by itself. There are many parameters that are unknown and change in unknown ways. So, the data sets used to train a ML algorithm will only allow that algorithm to tune up the accelerator in an approximate way. The hope is that a first ML optimization will, in general, tune the machine so that it is “close enough” for the ES algorithm to then tune the machine locally the rest of the way.

## James Rosenzweig: Ultra-compact XFELs using very high gradient cryogenic RF techniques and advanced undulators

This talk presented a compact XFEL concept using high-gradient, cryogenically cooled Cu structures. Achieving gradients of 500 MV/m, cyro-Cu structures would allow for much brighter electron beam sources and a much more compact accelerator. Combined with a short period undulator (1-10 mm), a MaRIE class XFEL could be located in a large room, rather than a 1 km long tunnel.

## Conclusion

From a bright beam generation perspective, we can sum things up in terms of short term, medium term and long term:

### Short term

The general consensus is that a MaRIE class XFEL can probably be built using an architecture very similar to that of the EuXFEL. Simulations show that the L-band photoinjector used by the EUXFEL can produce a bright enough beam and conventional compression schemes are good enough. The one outstanding question is the effect of long-range wakefields in the superconducting (SC) accelerating structures on beam quality. Because of the envisioned beam pulse format to be used at MaRIE, these could prove problematic and it is unclear our current numerical tools are adequate to predict their impact.

### Medium term

In the medium term, recent developments in cryo-Cu structures could have a very large impact on the design of a MaRIE class XFEL with modest R&D investment. Although very large accelerating gradients (100s of MV/m) are discussed with respect to cryo-Cu structures, an accelerator that ran reliably at only 50MV/m would have a large impact on MaRIE. At this average gradient, the MaRIE electron accelerator would fit into the existing LANSCE tunnel, which in turn would have large impacts on cost and schedule. In addition, development of cyro-Cu photoinjector technology, enabling 100s of MV/m accelerating gradient in the beam source, would lead to much brighter electron beams, reducing risk and possibly enabling the XFEL to lase at lower electron energy.

### Long term

In the long term, we can talk of large advances in cryo-Cu technology, leading to much more compact XFELs as envisioned in the talk by James Rosenzweig. Although we do not need such machines for MaRIE, we would certainly take them if available. However, considerable R&D resources would need to be brought to bear to realize this new technology.

## 5. Novel XFEL Physics and X-ray Optical Configurations WG Summary

We had nine talks in our two breakout sessions on Tuesday and Wednesday with lively participation. The breakout talks were all scheduled for 30 minutes, but discussion was so lively in each talk, they all went on for an average of 45 minutes. At the end of the session, there was more discussion. Our report considers each of the breakout talks as well as seven applicable talks in the plenary session.

**Plenary: Cris Barnes (LANL)** - The ambitious goals of the MaRIE project in 2025 include x-ray energies of 42 keV or greater from a 12 GeV accelerator with a very flexible x-ray pulse format and a peak of $10^{10}$ photons per pulse. Barnes stated that here is a mission need for science applied to manufacturing, especially in the dynamic mesoscale regime. These broad goals extend the whole x-ray field in the directions applicable to the future MaRIE project at LANL.

*We grouped the talks into topical areas starting with Compact X-Ray FELs including Bill Graves (AZ State University), Jamie Rosenzweig (UCLA), and Steve Benson (JLab).*

**Bill Graves (AZ State University)** - This is an ambitious university scale x-ray FEL sponsored by ASU using an optical undulator with a pre-bunched electron beam. We suggest that this project vigorously pursue numerical validation of the spatial-to-temporal electron beam bunching as well as the subsequent FEL emission of coherent photons in the optical undulator. This validation should precede and guide experimental development.

**James Rosenzweig (UCLA)** - This is also a university scale x-ray FEL but with high-gradient, cryogenic Cu accelerator achieving a gradient of 500 MV/m, followed by a short period (1-10mm) FEL undulator. Collaborators include SLAC, LANL, and INFN. A MaRIE "inspired" scenario is presented with simulation results showing 70 GW peak power in a 20 m undulator length using 100 pC, 5 ps electron pulses with 55 nm emittance. The cryo-undulator period used in this case was 9 mm with undulator parameter K=1.8.

**Steve Benson (JLab)** - A moderately compact x-ray FEL system was described using an Energy Recovery Linac (ERL) scheme designed to work at 1 GeV at MHz repetition rate known at DIANA. The project is a collaboration among JLab, Daresbury, MSU, and CERN, and plans to develop the source for lithography and the nuclear industry. DIANA will have 100 kW average power when operated in the EUV for the semiconductor lithography industry, but also a high-flux, narrow band inverse Compton scattering gamma source for nuclear physics, as well as precision electroweak measurements and dark matter searches.

*The next grouping of talks was describing novel X-FEL optical configurations, including only two speakers: Ken Evans-Lutterodt (BNL) and Yuri Shvyd'ko (ANL).*

**Ken Evans-Lutterodt (BNL)** - The fundamental physics of kinoforms, manufacturing methods, as well as experimental results, were described. The talk provided an excellent review of the now commercial product that is important for x-ray FELs and applications. There are hundreds of the x-ray lenses already in operation at a variety of x-ray sources. Today's kinoforms could already be useful for MaRie with the ability to focus high-energy x-rays to a small, high intensity spot. The project has several collaborators including Southern Illinois University, BNL, LANL, LNLS, and ANL.

**Yuri Shvyd'ko (ANL)** - Tunable, low-loss XFELO cavities are described with high-reflectivity Bragg crystal mirrors and transparent focusing elements. High-quality diamonds can have 99% reflectivity with meV bandwidths, with structural integrity withstanding 12 kW/mm$^2$ power intensity. The required angular stability of the long resonate cavity of the XFELO of 20 nrad (rms) can be achieved. Output coupling can be achieved through thin crystals allowing partial transmission, or mirrors with pinholes. A RAFEL cavity design with 90% outcoupling with a hole radius of 135 $\mu$m is described. Cavities are ready to be built for testing in a joint project between ANL and SLAC.

*Another grouping is of talks focused on using Novel Optical Cavities to improve the FEL brightness by either increasing the peak power or reducing the bandwidth. The performance improvements can also be used to increase the FEL spectral range. There were the six talks, listed below, in this grouping:*

1. *High Power and Brightness Double Bunch LCLS-II*, **Aliaksei Halavanau (SLAC)**
2. *XFELO: Performance and Prospects*, **Kwang-Je Kim (ANL)**
3. *Regenerative Amplifier X-ray FEL for the LCLS-II*, **Gabe Marcus (SLAC)**
4. *An X-ray Regenerative Amplifier Free-Electron Laser using Diamond Pinhole Mirrors*, **Henry Freund (CCR)**
5. *Regenerative Amplifier XFEL with a Thin Diamond as the Power Outcoupler*, **Dinh Nguyen (LANL)**
6. *Studies of a Terawatt X-ray Free-Electron Laser*, **Henry Freund (CCR)**

Many concepts using recirculation of the x-ray pulse to 'seed' the electron beam ranging from the XFELO, a low-gain, high Q optical cavity, to two-bunch seeding, a single pass recirculation. Although considered differently, these systems describe a continuum of recirculation options. In all cases, the recirculation improves x-ray performance over SASE significantly but all also have challenging optical systems based on crystals which was the topic described earlier in this summary. A SLAC/ANL R&D program is aimed at demonstrating the optical cavity and x-ray gain. In RAFEL and seeding cases, strong tapering can increase peak x-ray power. Studies of undulator and focusing requirements show the importance of strong focusing with short or nonexistent undulator breaks.

Two bunch self-seeding uses two closely spaced bunches in an undulator separated into two sections, the first to generate the seed, and, the second, to amplify it. The main bunch does not interact in the first undulator portion while the seed is generated by the other bunch. After a monochromator, the seed is recombined with main bunch in the second undulator section. By adjusting the delay of the monochromator, the seed can be generated by either the 1st or second electron bunch. The two bunch self-seeding provides a path towards high peak power and strong tapering with a fully coherent FEL pulse. The process is still subject to intensity fluctuations due to fluctuations in the seed generation.

The XFEL Oscillator (XFELO) could provide signal for HGHG seeding of MaRIE. XFELO works well at high harmonics. And it naturally produces very narrow spectrum x-ray pulses. R&D on the crystal optics for the optical cavity are ongoing with results expected in ~3 years.

The RAFEL concept resides between two-bunch seeding and XFELO with high gain FEL and low gain optical cavity. While tolerances and requirements should be looser than in the XFELO case because the FEL is operated in the high gain regime, there are still many challenges. One example is out-coupling. There were multiple suggestions at the workshop, ranging from tilted wave-fronts, deformable or holed mirrors, to thin diamond mirror configurations.

One of the challenges of MaRIE is the flexible bunch pattern where the spacing between bunches varies significantly along the macro-pulse. In this case, the two-bunch self-seeding might be most naturally suited to MaRIE as it can work with a very flexible bunch pattern to which the RAFEL and XFELO are less suited.

*The next grouping is of talks focused on using eSASE including simulation studies at LANL and experimental results at SLAC. There were the two talks, listed below, in this grouping:*

1. *eSASE as Bright Beam Compression for XFEL*, **Quinn Marksteiner (LANL)**
2. *High Intensity Attosecond X-ray Pulse Generation by Self-Modulation in a Wiggler*, **Zhen Zhang (SLAC)**

Quinn looked at using eSASE to ease constraints on the bunch compression process in MaRIE where the second bunch compressor (BC2) is a source of CSR and uBI dilution and RW wakes in the undulator reduce tapering effectiveness. In this implementation, the peak current is comparable to the peak current without eSASE however eSASE does the compression just before the undulator and so the CSR and uBI are reduced and the average current is reduced, decreasing the RW wakefield effect. The total photon count is down and the overall pulse length is greater but using a 2nd laser harmonic improves photon count to be comparable to cases without eSASE.

Zhen described experimental results from LCLS where eSASE was tried using a 2 $\mu$m laser and a ~4 GeV electron beam. The laser was challenging and a self-modulation technique based on coherent radiation from a trailing current spike was adopted to replace the laser. The eSASE increased the peak current by

~3x when using either the self-modulation from the trailing horn or current modulation from rf gun source laser. The focus at LCLS has been to generate sub-fs pulses but it would be useful to see whether there were also reductions in the gain length as might be hoped with the higher peak current.

*The next grouping is of talks focused on other novel concepts including a detailed study of limits in the EuXFEL when approaching 100 keV, a possible incoherent MeV-scale photon source, and a detailed simulation of CSR based on the Liénard–Wiechert formulation for the fields.*

1. *Towards 100 keV Lasing of the European XFEL*, **Evgeny Schneidmiller** and **Yuhui Li (DESY)**
2. *Gamma-ray Source based on Current Filamentation Instability*, **Vitaly Yakimenko (SLAC)**
3. *High Resolution Simulation of Classical Undulator Radiation Using the LW3D Code*, **Robert Ryne (LBNL)**

Broad set of topics including issues related to achieving 100 keV at the EuXFEL using the empty tunnels, generating MeV-scale incoherent photons with plasmas, and a code for detailed radiation calculations of undulator radiation or CSR.

## 6. Undulator Technology WG Summary

Six presentations where relevant for this session:

1. Y. Ivanyushenko (Plenary Talk):
   Superconducting undulator work at Argonne

2. Y. Li on behalf of Evgeny Schneidmiller (Plenary Talk):
   Towards 100 keV lasing of the European XFEL

3. Y. Li:
   Undulator parameter and technology studies for the ultra-high photon energy XFELs

4. J. Pflueger:
   European XFEL Undulator Systems: A Lead for MaRIE ?

5. T. Tanabe:
   Comparison of CPMU and SCU as High-energy and High-flux X-ray Free-Electron Laser’s Sources

6. H- D. Nuhn:
   LCLS-II Undulator System Tolerance Budget Analysis

## Y. Ivanyushenko: Superconducting undulator work at Argonne

In this invited talk an impressive overview over the SC undulator (SCU) development at the APS was given. Several planar devices with period lengths ranging from 16 to21mm were built and are in operation. Special emphasis was put on reliability of operation. Helical devices and crossed undulators are under development.
A comparison of present technology based of NbTi SCUs with Cryogenic In Vacuum undulators shows that with such an SCU higher fields can be obtained for periods lengths larger than about 14-15mm.
The on-going R&D program at APS includes:

- A fast-switching Super Conducting Arbitrarily Polarizing Emitter (SCAPE), (already in progress)
- Construction of a $Nb_3Sn$ prototype (already in progress)
- A feasibility study using High Temperature Superconductors (HTS) has been completed
- Ideas for long undulator systems as needed for XFELs;
- Multiple parallel undulators sharing one cryostat

SC may have a great potential for small period undulators.

## Yuhui Li on behalf of Evgeny Schneidmiller: Towards 100 keV lasing of the European XFEL

This presentation concentrated on the generation of Hard X-rays at the European XFEL with photon energies up to 100keV. Several proposals were presented. One used about 100m of 5m long U40 type undulators with 40mm period length as already in use in SASE1/2 in combination with 30m of undulators with 30mm period length tuned to high harmonics, which may use EuXFEL technology. For a normalized emittance of 0.2 $\mu$m photon energies higher than 60keV can be reached on the fundamental and more than 100keV using the third harmonic. In general 3$^{rd}$ harmonic lasing in combination with retuning the phase shifters to the 3$^{rd}$ harmonic and suppress the first harmonic is a powerful tool to reach high photon energies.

An even higher performance can be obtained by a combination of a smaller gap of 7mm, a U35 and U27 using conventional technology and a short SC undulator of 20mm period length.

Another proposal is to use the afterburner principle and inverse tapering. It preserves the micro-bunching but strongly suppresses FEL light emission of the long undulator. This reduces energy spread. In the afterburner the micro bunched electron beam emits coherent radiation. The afterburner principle was already demonstrated at FLASH and SASE3 of the EuXFEL. For the afterburner a short period undulator can be used to radiate hard X-ray radiation.

Alternative methods of light generation were discussed:

- Nonlinear harmonics generation, which is always present.
- High harmonic lasing self-seeding (HLSS)
- Cascaded frequency multiplication
- Multi-stage optical klystron requiring chicanes

These are interesting options for the European XFEL.

## Y. Li: Undulator parameter and technology studies for the ultra-high photon energy XFELs.

The tuneability of photon energy ranges for different undulator technologies, permanent magnet (PM) undulators, In-Vacuum PM undulators (IVUs) was studied. At 17.5GeV an SCU with 21mm period length can be tuned from 0.15 to 0.45Å, and an SCU with 18mm period length from 0.12 to 0.2Å. Using the same period length the other magnet technologies result in a smaller tuning range.

Third harmonic generation was investigated. The saturation power of the 3$^{rd}$ harmonic of the existing SASE1/2 without modification at 0.15Å is already 3x$10^9$ W, about one-seventh of the 2x $10^{10}$ W power in the fundamental at 0.45Å.

The fundamental can be suppressed by systematically de-tuning the phase shifters. Different schemes were investigated. This principle can be further improved using shorter undulator segments and accordingly more phase shifters. The emittance of the electron beam has a large impact. An example using 2.5m long U40 segments and a zero emittance beam showed that after about 110m the 1$^{st}$ harmonic at 0.45 Å could be reduced to 5 x $10^8$ W, while the 3$^{rd}$ harmonic is increased to 6 x $10^9$ W thus reversing the intensity ratio of 1$^{st}$ and 3$^{rd}$ harmonics.

## J. Pflueger: The European XFEL (EuXFEL) Undulator Systems: A Lead for MaRIE ?

The European XFEL is a worldwide unique facility: It has the highest energy, 17.5 GeV and undulator systems which are up to 213.5m long. Like many other XFEL facilities it is using out of vacuum technology and extruded vacuum chambers thus losing only 1.5mm due to chamber wall thickness.

The pros and cons of undulator technologies were shortly assessed: IVU technology is most commonly used for SASE-FELs: FLASH, LCLS I, Pohang XFEL European XFEL, LCLS II.
IVU technology is used for SACLA and SwissFEL.
CPMU technology has not yet been used for long undulator systems. However a project is discussed at SOLEIL. SCU technology is being discussed. Shorter period length and high fields would open more options. R&D is needed to develop the technology for long systems as needed for XFELs.

Wavelength tuneability is an important design parameter with significant impact on the total length of a system.

Based on the EuXFEL out-of-vacuum technology, the first estimates were made assuming MaRIE beam parameters: E=12GeV; $\varepsilon_n$=0.2µm; $I_p$=5000A; $\Delta$E=1.8MeV. It was shown that the following photon energy ranges might be accessible:

$\lambda_{Rad}$: 0.3 - 0.6Å (20- 41keV) $\lambda$=23mm; magnetic gap 7mm; magnetic system length $\approx$ 76m
$\lambda_{Rad}$: 0.25 - 0.5Å (25-50keV) $\lambda$=21.8mm; magnetic gap 7mm; magnetic system length $\approx$ 100m

Shorter wavelengths may become accessible using new technologies.
Due to the improved beam parameters the gain lengths are shorter than for EuXFEL. It is concluded that improved beam parameters are an effective way to shorten the gain and saturation length of an undulator system.

Radiation damage can be controlled Following the EuXFEL way: A dog leg, collimators, online dosimetry, and advanced beam operation.

## T. Tanabe: Comparison of CPMU and SCU as High-energy and High-flux X-ray Free-Electron Laser's Sources

An assessment of observed Radiation Damage of IVUs in storage rings and FELs has been made. Special emphasis was given to the large radiation damage observed on the IVU at SACLA.

Radiation damage in SC materials has also been reported: Reference was given to the Workshop on Accelerator Magnets, Superconductor, Design and Optimization, Geneva, 14. November 2011. Here moderate damage was observed in NbTi , but significant damage in $Nb_3Sn$ SC material.

Recent developments for IVU and CPMU include methods for force compensation using compensation by springs or compensating magnets producing repulsive fields.
So far the length of CPMUs are typically limited to <= 2m. At Soleil there are plans to use for the first time a CPMU based undulator system.

An interesting application for 9mm periods and 2.5mm gap and a peak field og > 1.1T use in a Laser Accelerator.

## H- D. Nuhn: LCLS-II Undulator System Tolerance Budget Analysis

The systematic way was described how the total error budget for the LCLSII undulator systems was set up. The influence of many parameters on FEL performance was studied. Their tolerances have to be found so that these errors sources have a balanced impact on FEL performance.
This problem arises when there are many parameters with impact on performance for which tolerances have to be found.
It is a "Must Do" for a complete design of undulator systems such as LCLSII.

## Conclusion

Undulators are indispensable parts of X-ray FELs. The workshop gave a good overview over various applications. Undulator technology has been further developed and has made good progress. While CPMUs and/or SCUs may be used for future projects so far all XFELs in operation rely either (out of vacuum) PM or IVU technology.

For MaRIE Out of Vacuum PM technology offers a low cost, low risk solution to cover the photon energy range up to 50-60 keV (0.2-0.25Å).
Third harmonic lasing schemes eventually in combination with SC undulators may further extend the photon energy range well beyond this photon range.

In summary there are several options for undulator technologies to meet potential requirements for MaRIE depending on scientific requirements, R&D effort, budget and available time.

## 7. Appendix A – Organizing Committee

**Chair:**
Dr. Dinh Nguyen (Los Alamos National Laboratory)

**Co-Chair:**
Dr. Joachim Pflueger (retired European X-ray FEL)

**Secretariat:**
Ms. Lucy Maestas (Los Alamos National Laboratory)

**Protocol Coordinator:**
Ms. Peggy Vigil (Los Alamos National Laboratory)

**Web Page Coordinator:**
Ms. Sarah Haag (Los Alamos National Laboratory)

**Working Groups Chairs:**
**Bright Beam Generation, Acceleration and Manipulation WG**

Drs. Steven Russell and Kip Bishofberger (Los Alamos National Laboratory)

**Novel XFEL Physics and X-ray Optical Configurations WG**

Drs. William Colson (WBC Physics) and Tor Raubenheimer (SLAC)

**Advanced Undulator Technologies WG**

Drs. Joachim Pflueger (retired European X-ray FEL) and Dinh Nguyen (Los Alamos National Laboratory)

# 8. Appendix B – List of Attendees

| Last Name | First Name | Company Name |
|---|---|---|
| Anisimov | Petr | Los Alamos National Laboratory |
| Badura | Kaelyn | Los Alamos National Laboratory |
| Barnes | Cris | Los Alamos National Laboratory |
| Benson | Stephen | Jefferson Laboratory |
| Bishofberger | Kip | Los Alamos National Laboratory |
| Bohon | Jen | Los Alamos National Laboratory |
| Byrd | John | Argonne National Laboratory |
| Colson | William | WBC Physics |
| Dunham | Bruce | SLAC National Accelerator Laboratory |
| Evans-Lutterodt | Kenneth | Brookhaven National Laboratory |
| Fazio | Michael | SLAC National Accelerator Laboratory |
| Freund | Henry | Calabazas Creek Research |
| Halavanau | Aliaksei | SLAC National Accelerator Laboratory |
| Huang | Chengkun | Los Alamos National Laboratory |
| Ivanyushenkov | Yury | Argonne National Laboratory |
| Kim | Kwang-Je | Argonne National Laboratory |
| Li | Derun | Lawrence Berkeley National Laboratory |
| Marcus | Gabriel | SLAC National Accelerator Laboratory |
| Michaudon | Andre | Los Alamos National Laboratory |
| Nguyen | Dinh | Los Alamos National Laboratory |
| Pflueger | Joachim | European XFEL (retired) |
| Raubenheimer | Tor | SLAC National Accelerator Laboratory |
| Robles | River | UCLA |
| Rosenzweig | James | UCLA |
| Ryne | Robert | Lawrence Berkeley National Laboratory |
| Scheinker | Alexander | Los Alamos National Laboratory |
| Sheffield | Richard | Los Alamos National Laboratory |
| Shvyd'ko | Yuri | Argonne National Laboratory |
| Szymanski | John | Los Alamos National Laboratory |
| Tanabe | Toshiya | Brookhaven National Laboratory |
| Tantawi | Samy | SLAC National Accelerator Laboratory |
| Yakimenko | Vitaly | SLAC National Accelerator Laboratory |
| Yuhui | Li | European XFEL GmbH |
| Zhang | Zhen | SLAC National Accelerator Laboratory |