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THE PHYSICS AND APPLICATIONS OF HIGH BRIGHTNESS BEAMS: WORKING GROUP C SUMMARY ON APPLICATIONS TO FELS*

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Working group C, "Application to FELs," of the Joint ICFA Advanced Accelerator and Beam Dynamics Workshop on July 1-6, 2002 in Chia Laguna, Sardinia, Italy addressed a total of nine topics. This summary will discuss the topics that were addressed in the stand-alone sessions, including Start-To-End Simulations, SASE Experiment, PERSEO, "Optics Free" FEL Oscillators, and VISA II.

1. Introduction

This is the summary of the activities in working group C, "Application to FELs," which was based in the Bithia room at the Joint ICFA Advanced Accelerator and Beam Dynamics Workshop on July 1-6, 2002 in Chia Laguna, Sardinia, Italy. Working group C was small in relation to the other working groups at that workshop. Attendees include Enrica Chiadroni, University of Rome "La Sapienza", Luca Giannessi, ENEA, Steve Lidia, LBNL, Vladimir Litvinenko, Duke University, Patrick Muggli, UCLA, Alex Murokh, UCLA, Heinz-Dieter Nuhn, SLAC, Sven Reiche, UCLA, Jamie Rosenzweig, UCLA, Claudio Pellegrini, UCLA, Susan Smith, Daresbury Laboratory, Matthew Thompson, UCLA, Alexander Varfolomeev, Russian Research Center, plus a small number of occasional visitors.

The working group addressed a total of nine topics. Each topic was introduced by a presentation, which initiated a discussion of the topic during and after the presentation. The speaker of the introductory presentation facilitated the discussion.

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There were six topics that were treated in stand-alone sessions of working group C. In addition, there were two joint sessions, one with working group B, which included one topic, and one with working group C, which included two topics. The presentations that were given in the joint sessions are summarized in the working group summary reports for groups B and D, respectively. This summary will only discuss the topics that were addressed in the stand-alone sessions, including Start-To-End Simulations, SASE Experiment, PERSEO, "Optics Free" FEL Oscillators, and VISA II.

1.1. *Start-To-End Simulations*

The first presentation in working group C was by Sven Reiche about the status of start-to-end simulations. With the development of high-brightness electron beam sources and short wavelength SASE free-electron lasers, the need arises to parameterize the electron beam on a much more detailed level than projected beam quantities such as energy spread or emittance. This is done by start-to-end simulations, where an electron bunch is tracked from its generation in an RF photocathode gun to the exit of the undulator. The presentation summarized the methods that used for the recent start-end simulations and gave an outlook on the trends for the near future.

Sven Reiche pointed out that a SASE FEL system consists of quite a number of different subsystems in which different processes take place. These subsystems are: the drive laser, the RF gun, the linac sections, the bunch compressors, the FEL undulators, and the FEL beam optics. There is no single code that covers the entire system and it is felt that it is not necessary or desirable to create such a code. Instead, there are different codes for each subsystem that handle the different processes in that subsystem. The codes are modules in a modular system. All modules, except the first, work on the output of the preceding module, which is stored in data files. The results of the computations are in-turn stored in data files, again, to be picked up by the following module. So far, the start-to-end simulations have been done with modules for the gun, the linac sections, the bunch-compressors, and the FEL undulator. It is desirable to add modules for gun laser, multi-stage FELs and FEL optics components.

The actual computer codes used as modules are listed in the table:

Table 1 Start-to-end simulations codes

Drive Laser	None
Gun	Astra, Parmela
Linac	Elegant
Bunch Compressor	Traffic4, (Elegant)
FEL	Genesis 1.3, Ginger, Fast
FEL Optics	SRW, Phase, R.Bionta@LLNL, Shadow

No code is available yet that would allow simulating the drive laser. For the RF photocathode gun there are Astra by a group at DESY and Parmela by Lloyd Young at Los Alamos. For the linac, the code Elegant by Michael Borland from Argonne is used. For the bunch-compressor calculations, which are mostly concerned with the handling of coherent synchrotron radiation (CSR), there is Traffic[4] from DESY and also Elegant contains a 1-D treatment of CSR. The predominant time-dependent FEL codes are Genesis 1.3 by Sven Reiche from UCLA, Ginger by William M. Fawley from LBNL, and FAST by Evgeny Saldin, Evgeny Schneidmiller and Michael Yurkov from DESY.

Several codes exist or are being developed for the FEL optics, some at BESSY and the ESRF and some at LLNL by Richard Bionta and co-workers. Those codes are not yet directly coupled to the rest of the modules but there are plans to do this.

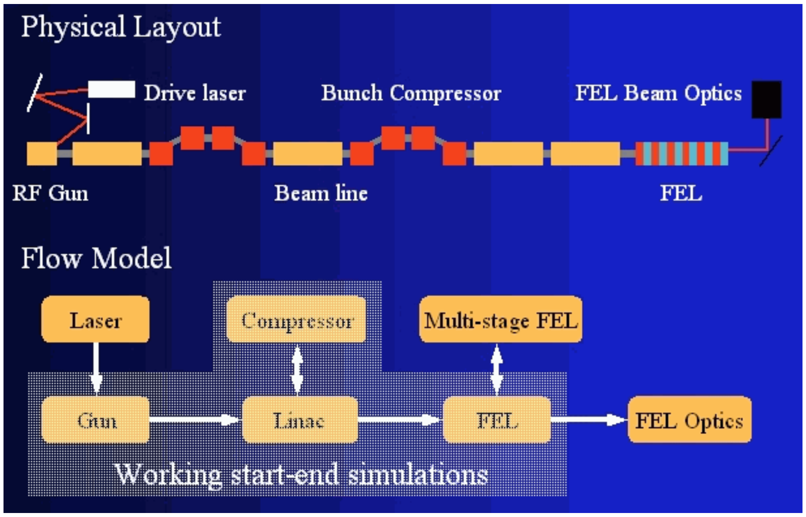

Figure 1 The start-to-end model.

Important is the file format used to exchange results between the various modules. In the past, applications have been written in native file formats. This means that the authors just invented a new set of input and output formats every time they wrote a new code. Of course, different programs used completely different formats. In order to be able to exchange data from one code to another one needed to write a translator code to convert between the formats. These special formats are difficult to maintain. Often, it is even difficult for the authors themselves to remember what the exact input format was. The format is normally fixed, meaning that, for instance, the numbers have to be put into a certain range of columns in the input line or either must or must not contain a decimal point. If errors are made the programs may read the numbers wrongly, which is often difficult to catch by the user. The input and output files are normally so specialized that preprocessor and postprocessor programs have to be distributed together with the module code itself in order to produce and/or read these files. No standard software is able to read these files.

This is different with the new approach of using Self Describing Data Formats. The start-to-end effort is using the SDDS (Self Describing Data Set) system developed by Michael Borland at Argonne. The files that are produced, maintained, and evaluated by this package do not only contain the data themselves but also a description of the data, i.e., the names, the physical units and even the format in which the data is coded. The programs are storing the data in ASCII as well as in binary format. There are functions available that can convert from one format to another. The SDDS system provides a large number of library functions to be used by code developers and there is a toolkit for processing and plotting the data. Using Self Describing Data Format tools greatly simplifies the flow in start-to-end simulations and Michael Borland's SDDS set is particularly good for homogeneous data sets. Sven Reiche pointed out that there are desirable aspects that are still missing in Michael Borland's SDDS system. In particular, SDDS does not validate files against a given format

Over the last several years, a more general Self Describing Data Format, which is called the Extensible Markup Language (XML), has been developed by international groups completely independent from the accelerator community. XML provides significantly better control over the data and makes it possible that the data validity can be checked by generic codes. Sven Reiche made a strong pledge for using this system.

Under XML, the files are well formatted, validated, and platform independent. Various software libraries and editors are available. The system is widely used, outside of the accelerator community. The data organization in the files is so that generic programs can handle the data. The system allows for flexible transformation between various user-defined formats. One of the drawbacks is that there is a large overhead for long, similar data sets, such as large lists of particle phase space information. When storing these kinds of data, the data files would be of an enormous size because the storage is in ASCII and there is a description for each number. XML seems not to support binary formats in a controlled way. The SDDS system does a better job for those large data sets.

Sven Reiche believes that the equivalent for XML for binary data sets would be the Hierarchical Data Format Version 5 (HDF5). The HDF5 software is developed and supported by NCSA and is freely available. It is used world-wide in many fields, including Environmental Science, Neutron Scattering, Non-Destructive Testing, and Aerospace, to name a few. Scientific projects that use HDF5 include NASA's HDF-EOS project, and the DOE's Advanced Simulation and Computing Program. Sven Reiche will examine this option.

The next step in the development of the start-to-end simulation should be the addition of the FEL optics module, the improvement of the support for a standardized format, extension of the common file format to all major data streams, automation and automatic checking of the input data, and support for scripted execution of the entire system. The latter is important because the separate modules have long execution times. Scripted execution allows for them to run in the background without need for intermittent attention from the user.

In addition, the development of user friendly GUIs, built on top of scripted shells, are desirable because they would make it easier to distribute the packages to other users.

1.2. *SASE Experiments*

The next topic was introduced by Alex Murokh, who summarized what has been learned from the SASE experiments.

Three major SASE experiments have been successfully carried out in the last few years: LEUTL at Argonne, the TTF-FEL at DESY and VISA at the ATF at Brookhaven. VISA was carried out by a collaboration of a number of laboratories including the LCLS.

Alex Murokh found that there was a lack of detailed measurements of particle distributions at the input to the undulator. The VISA experiment had done the best job in simulating the distribution. The other two experiments had large uncertainties for average parameters such as emittance.

During the evaluation of the experimental data it became clear that one could only fully analyze the FEL experiments when using simulation codes, because the particle phase space distributions, used in the experiments, are too complicated to be reasonably describable by analytic theory. It is still necessary that detailed measurements of particle distributions be made in order to check the simulations at a number of positions along the system.

All three experiments worked with rather complicated distributions, which, in the case of VISA, could be simulated, and the measured results agreed with the simulations to an amazing degree.

If the experiments could be made with simpler distributions it would be easier to measure the distributions experimentally. This would also make these results more available for the comparison with analytical theory.

Alex Murokh looked at 3-D scaling laws to test if parameters that were measured at VISA scaled as the theory predicts. He is planning to do this also for the other two experiments as soon as he gets sufficient data. In order to check the 3-D scaling laws, Alex Murokh estimated the effective FEL parameter, ρ, from the measured gain length According to

$$L_g \approx \frac{\lambda_u}{4\pi\sqrt{3}\rho}. \tag{0.1}$$

Once ρ is estimated from the measured gain length, a number of parameters can be calculated such as the saturation length, the spread of the saturation lengths over many pulses, the saturation power, the bandwidth, the corporation length, the gain at saturation, and the noise bandwidth. These parameters can also all be obtained independently from the experimental results. Alex Murokh compared the results of these two approaches and came to the conclusion that the agreement is rather good.

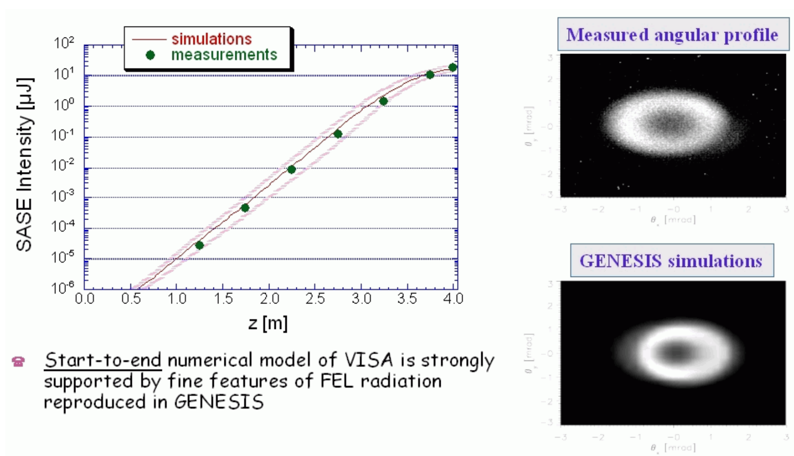

Figure 2 Results of start-to-end simulations for the VISA experiment.

As already mentioned, the main part of the VISA experimental analysis was based on intense start-to-end simulations. Results from these simulations include the prediction of the gain development along the undulator. The measurements agreed very well with the predicted gain curve.

One of the results, caused by the complicated phase space distribution in the VISA experiment, was a donut shaped distribution of the FEL radiation at the exit of the undulator. It is one of the satisfying successes of start-to-end simulations that even the radiation pattern of such a complicated phase space distribution can be predicted and explained by start-to-end simulations. This and a number of other points give very good confidence to the simulation codes.

1.3. *PERSEO*

The next contribution was by Luca Giannessi. He introduced his tool set, PERSEO, for FEL simulations using the commercial MathCAD package[c]. Luca Giannessi wrote a suite of complex functions in the C language that can be called from MathCAD and allow the 1-dimensional simulation of SASE FEL configurations. He also wrote a number of MathCAD scripts that use these functions and provide more complex functionality. He showed an example where he demonstrated how to seed the phase space, solve the pendulum equation, and produce graphical displays of both the initial and final phase space distributions. He also demonstrated how one could very easily instruct MathCAD to generate a movie interactively by selecting a set of graphics, and specifying a parameter, the parameter's range and the step size.

Luca Giannessi maintains a WEB site[d] from which the code can be downloaded to one's own computer and installed there. The site also contains examples for the use of the package.

[c] http://www.mathcad.com/products/mathcad.asp

[d] http://www.afs.enea.it/gianness/perseo/

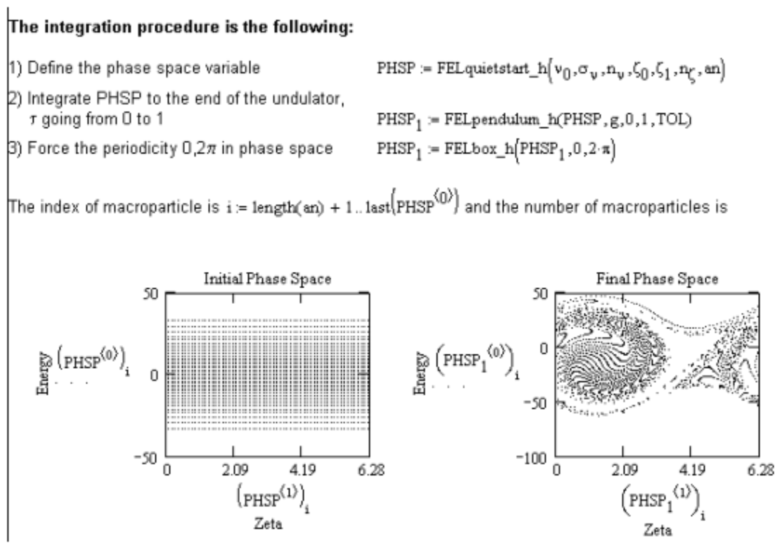

Figure 3 Example for using the PERSEO system.

1.4. *"Optics Free" FEL Oscillators*

The next presentation was by Vladimir Litvinenko about "Optics Free" FEL Oscillators. Vladimir Litvinenko addressed the problem that the spectral distribution of radiation from SASE FELs is rather wide, i.e., on the order of 0.3-0.5 % while typical VUV FEL oscillators, such as the OK-4 at Duke University, have a much smaller bandwidth of 0.01-0.0003%. Of course, the absence of good optics in the VUV and X-Ray spectral ranges makes traditional oscillator schemes prohibitory complex or impossible. That is why Vladimir Litvinenko introduces the concept of optics-free FEL oscillators. The basic idea is to use a high gain FEL, which produces a radiation pulse that can be used for experiments and, at the same time, can also be used to add a momentum modulation to a low energy feedback electron beam that travels through a small modulator undulator together with the radiation pulse. The feedback beam is produced by an independent electron source and is longer than the radiation pulse. Only the part of the feedback beam that overlaps with the radiation pulse will be modulated. The modulated feedback beam is then transported through an isochronous beamline to the beginning of the high-gain FEL where it enters a small radiator undulator to produce seed light for seeding the FEL process for the next arriving electron bunch entering the high-gain FEL (See Figure 4).

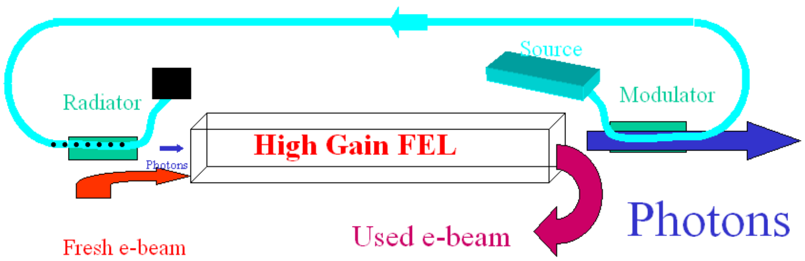

Figure 4 System diagram of the "Optics Free" FEL Oscillator.

Of course, the seed light amplitude needs to be larger than the noise power produced by the next bunch at the beginning of the high-gain undulator and there has to be a large temporal overlap between the seed light and the modulated part of the feedback beam. If the temporal jitter of the incoming electron bunch is larger than its width the scheme will not work. To overcome this problem one could work with a train of bunches that are temporally spaced by the same time that it takes for the electron bunch to travel through the feedback undulator and for the feedback beam to be transported back to the radiator undulator. These bunches would have very little time jitter with respect to each other. This might make such a scheme possible.

In order for the system to function, the momentum modulation in the feedback beam must be preserved during the transport from the modulator undulator to the radiator undulator. One condition is that the beamline needs to be isochronous, i.e., the momentum compaction factor needs to be fairly small up to higher order. Vladimir Litvinenko calculated limit values of 10^{-8} for the first order, 10^{-4} for the second order and 1 for the third order of the momentum compaction factor. Effects of emittance increase need to be compensated by sextupoles that are positioned inside the achromatic arcs.

The main limiting factor are quantum fluctuations due to synchrotron radiation in the transport bending magnets, setting an upper limit to the energy of the feedback beam. Vladimir Litvinenko believes that the scheme is still doable. He calculated that the dimensions of the radiator undulator could be 6 cm in length for 100 periods with a period length of 0.6 mm. With an energy of

500 MeV, an intensity of about 1 A and a normalized emittance of 0.1-0.3 mm mrad the oscillator gain could be as high as 10^3-10^4.

So far, effects such as CSR, the stability of power supplies, and the limited quality of the magnets have not been taken into account. The low current and the small emittance provide for "toy sizes" of the magnetic components in the arcs.

1.5. *Recirculating Linac Facility*

The next topic was presented by Steve Lidia, an initial conceptual design for a femto-scale pulse length synchrotron radiation facility ('femtosource'). The facility, planned at LBNL, is based upon a recirculating linac, which is being designed to generate flat electron beams of 2 ps duration in a series of conventional undulators and bend magnets. There is a strong scientific case for time resolved experiments at time scales of the order of atomic vibration levels of about 100 fs.

Starting from an injector system the beam makes several passes through a number of linac sections as shown in Figure 5. Between passes, the beam is transported by several beam transport lines with increasing radii. After the fourth pass through the linac the electron beam goes through a sequence of radiators, i.e., an alternate array of insertion devices and bending magnets that produce radiation that can be adjusted over a range between 1 and 10 keV. The x-ray pulses are expected to be shorter than 100 fs FWHM at 10 keV. The proposed repetition rate is quite high at 10 kHz. The goal for the photon flux is 10^7 photons/pulse/.1% BW at 10 keV. The proposed level of synchronization is 10 fs.

The system is to be incorporated in the LBNL laboratory close to the Advance Light Source.

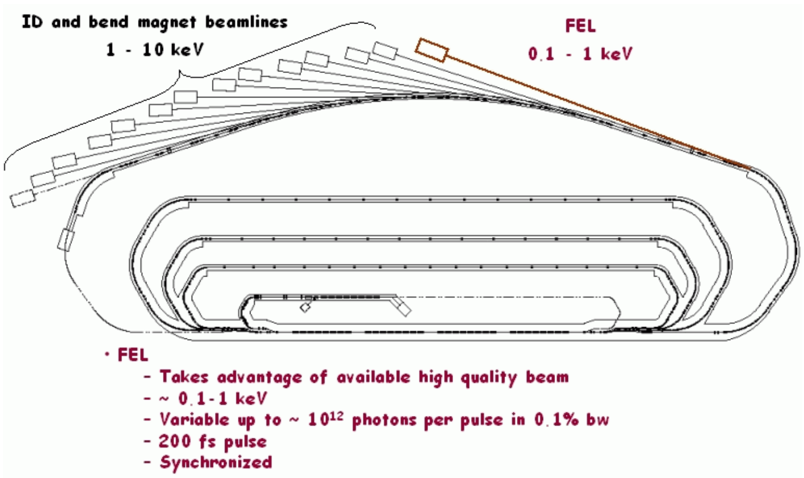

Figure 5 The components of the planned recirculating linac facility with ID and bend magnet beamlines as well as a soft x-ray FEL.

The presentation included a description of the general parameters of the facility, emphasizing the use of existing technologies along with those now in development. The generation of the flat electron beam from a novel RF photoinjector and a skew-quadrupole transport line were described, and recent experimental results, confirming the basic theory, were presented. Emittance preservation techniques for the linac and the recirculating arcs, by proper betatron tune phasing against the single bunch transverse wakefields, were mentioned. Facility infrastructure, cryogenic plant and RF power requirements were presented.

Of particular interest for the SASE FEL community is the development of the photocathode RF gun with pulse repetition rates of 10-100 kHz producing an 8-MeV electron beam. Through a workshop on New Opportunities in Ultrafast Science using x-rays, the group at LBNL established that there is strong scientific interest for the facility. Their outline of the machine feasibility was backed by a Machine Technical Advisory Committee. They plan to document the scientific case and the machine feasibility this year to put the Femtosource on the BESAC agenda. They need to develop mastery of technologies outside the present core competencies of the lab.

1.6. *VISA II*

The last topic, VISA II, was presented by Jamie Rosenzweig and Claudio Pellegrini. VISA, which stands for Visible-to-Infrared-SASE-Amplifier, is an experiment that has been developed and installed at the Accelerator Test Facility (ATF) at BNL from 1998 to 2001. The experiment produced outstanding results in 2001. The experiment has been featured at the SSRL home page[e] as Research Highlight[f] for the month of June 2002. Funding for VISA stopped in mid-2001.

In order to continue the studies, a group from UCLA and BNL joint and submitted a proposal for continuing studies, called VISA II, to the Office of Naval Research (ONL). Funding for the proposal has already been granted at a level of $300k this calendar year plus additional funding in the following years. The plan is that a collaboration of UCLA, SLAC and BNL continue VISA experiments.

VISA measured a large range of phenomena, including exponential gain at saturation, photon statistics, radiation spectra, and micro-bunch using CTR. The operating point was somewhat pathological, making use of strong bunch compression due to the non-linear properties of ATF beamline 3.

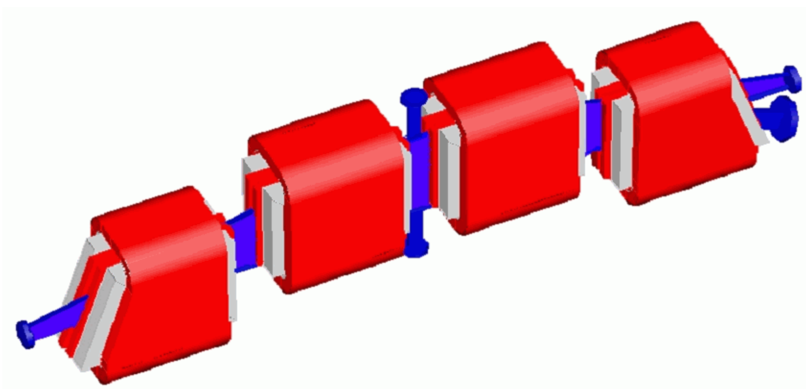

Figure 6 3-D Rendering of the new bunch compressor chicane recently installed in the ATF.

[e] http://www-ssrl.slac.stanford.edu/
[f] http://www-ssrl.slac.stanford.edu/research/highlights_archive/visa.html

The system was extremely sensitive to RF phase jitter and the information of the initial longitudinal phase space distribution from the gun was completely lost in the non-linear beamline. There is interest of doing a more linear experiment using a desired longitudinal phase space distribution. This is where VISA II comes in.

Part of VISA II is the commissioning of the recently installed linear ATF bunch compressor (see Figure 6). The next step will then be to mitigate the severe nonlinearities in the existing beam by inserting sextupoles (2 might be enough, the study is on-going). And finally add more diagnostics to the beginning of the undulator to better characterize the beam.

Once the system is running, studies can be done with compressed and with uncompressed but chirped beams. Using compressed beams, the system can be used to diagnose the new bunch compressor. With uncompressed but chirped beams the impact of chirped beams on FEL gain can be studied. This will be in support of the LCLS, for which schemes have been proposed that use momentum chirping to produce short x-ray pulses. The chirped beam can also be used as direct diagnosis of FEL longitudinal pulse characteristics.

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