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FACET-II Science Workshop Summary Report

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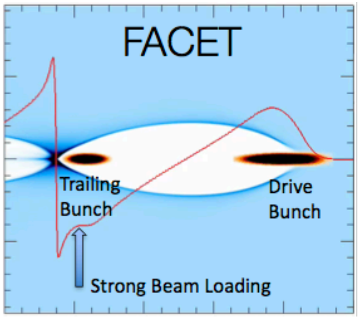

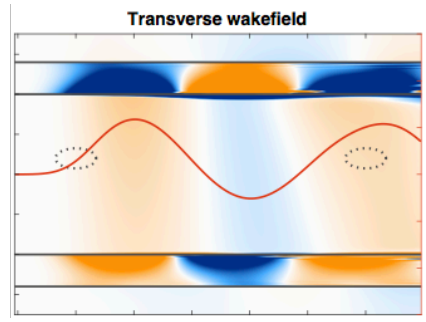

FACET-II Science Workshop Summary Report

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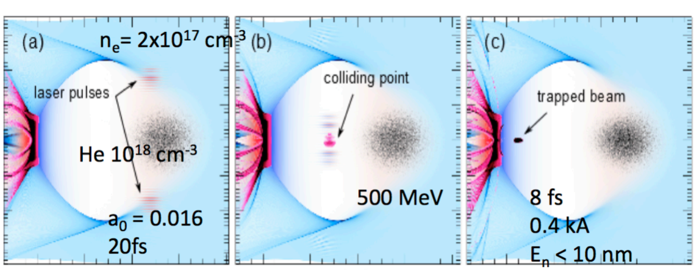

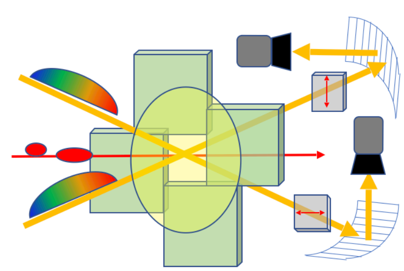

1. Summary

The Third in a series of FACET-II Science Workshops was held at SLAC National Accelerator Laboratory on October 17-20, 2017 [1]. The workshop drew sixty-four participants from twenty-three different institutions including ANL, BNL, DESY, DOE, Ecole Polytechnique, FNAL, IST, JAI, LBNL, Princeton, Radiabeam, Radiasoft, SLAC, Stony Brook, Tech-X, Tsinghua University, UC Boulder, UCLA, UT Austin, University of Chicago, University of Oslo, University of Pennsylvania, University of Strathclyde and University of Victoria. The 2015 workshop [2, 3] helped prioritize research directions for FACET-II. The 2016 workshop was focused on understanding what improvements are needed at the facility to support the next generation of experiments [4, 5]. The focus of the 2017 workshop was to assess and chart the development of key technologies needed to execute the envisioned FACET-II science program. All presentations are linked to the workshop website as a permanent record and the full agenda is listed in Appendix A.

https://conf.slac.stanford.edu/facet-2-2017/

2. Day 1:

2.1 Introduction

The 2017 FACET-II Science Workshop was the third in a planned series of annual workshops organized to optimize the impact of the FACET-II science programs. The DOE Advanced Accelerator Strategy Report defined a series of milestones for progress in advanced acceleration technology. These milestones lay out the most important areas of focus for the FACET-II facility. They include preserving beam quality and emittance, identifying techniques for positron acceleration in plasmas, developing plasma injectors as sources of ultra-low emittance beams and demonstrating staging.

The timeline for FACET-II has nominal electron beam parameters (10GeV, 2nC, 15kA, 30Hz) available in 2019 and nominal positron parameters (10GeV, 1nC, 6kA, 5Hz) in 2021. FACET-II is expected to operate 6 months per year. Experimental scheduling will have to balance the increased reliability and flexibility of the photoinjector against less frequent tunnel access when LCLS-II is in operation.

The major themes of the workshop followed the agenda given in Table 1 of Appendix A.

2.2 FACET-II Accelerator Introduction

The baseline design of the FACET-II accelerator complex is now rather mature, having been studied in start-to-end simulations in multiple configurations. Each aspect has been peer-reviewed on multiple occasions over the past three years. During this time, there have been many optimizations to the design. Possible future upgrades have been studied and their performance improvements modeled. It has become apparent that the high-brightness injector allows an impressive flexibility in operational parameters over and above what was achievable at FACET. Operational parameters span a range from the 'signature' 2-bunch notched beam configuration used for driving plasma experiments at FACET, to very highly-compressed multi-100 kA peak current electron bunches in Sector 20. The discussion covered various operational modes and trade-offs between longitudinal and transverse phase-space quality on delivery to the Sector 20 experimental region. This improves the planning for future beam experiments. A particular topic of keen interest to the experimental groups at this and past meetings is how to improve beam quality (achieve smoother, more Gaussian distributions in 5D space) at high peak longitudinal compression. Groups at SLAC and BNL presented work on optics design modifications to reduce CSR degradation in the BC20 chicane system and improve chromatic aberrations in the Sector 20 final focus system. These included new compressor designs that either reduce or actively compensate for CSR aberrations and updated final focus system layouts that lead to greatly smoothed Gaussian profiles at the experimental beam waist.

A major achievement during the FACET-II design studies has been the assembly of a parallelized start-to-end tracking simulation environment to characterize the dynamic behavior of the beam delivered to Sector 20 experiments. This is an important input for planning experiments to understand the expected operational fluctuations of key deliverable beam parameters. The users were presented with expected operational conditions for several parameter configurations as well as possible upgrade scenarios. Feedback from the user groups is a key component to understanding where to focus future upgrade efforts.

FACET used thin windows to protect the Sector 20 vacuum from the experimental region. Given the greatly improved longitudinal brightness of the FACET-II beam, it is desirable to replace the windows with differential pumping. A possible pumping solution was presented, with early implementation focused on meeting the requirements of plasma experiments with a Li oven. There were also discussions of ongoing work to consider a pumping solution suitable for all Sector 20 experimental users. The different pumping solutions can potentially impact beam dynamics, so continuing work is needed to arrive at a completely optimized solution.

2.3 Proposals Taking Shape for First Experiments

During the past two decades of research, the ultra-relativistic beam-driven plasma wakefield accelerator (PWFA) concept has achieved many significant milestones. These include the demonstration of ultra-high gradient acceleration of electrons over meter-scale plasma accelerator structures, efficient acceleration of a narrow energy spread electron bunch at high-gradients, positron acceleration using wakes in uniform plasmas and in hollow plasma channels, and the demonstration that highly nonlinear wakes in the “blow-out regime” have the electric field structure necessary for preserving the emittance of the accelerating bunch. A new 10 GeV electron beam facility, FACET-II, is currently under construction at SLAC for next generation PWFA research. The FACET-II beams will be able to simultaneously demonstrate substantial energy gain of a small emittance electron bunch with a high transfer of energy from the drive to the trailing bunch. The planned series of PWFA experiments are designed to demonstrate plasma wake generation where the drive beam is nearly depleted of its energy, high efficiency acceleration of the trailing bunch while doubling its energy and ultimately, quantifying the emittance growth in a single stage of a PWFA that has optimally designed matching sections.

The next decadal challenge [6] for the plasma accelerator community is to demonstrate a single stage of a multistage plasma based tera-electron-volt (TeV) scale accelerator. Preliminary design of a beam-driven plasma accelerator-based linear collider envisions that each plasma stage should increase the energy of the accelerating bunch by 10 GeV and preserve its ultra-low emittance while nearly fully depleting the drive bunch energy [7]. FACET-II [8] is being constructed to support the R&D for such a future facility.

A future linear collider operating at the frontier of particle physics is both a scientific and engineering grand challenge for this century [9]. In 2016, the U.S. Department of Energy’s Office of High Energy Physics (DOE-HEP) arranged a workshop to develop a long-range strategic development plan for advanced acceleration R&D [10]. This report laid out milestones to optimize the use of the various facilities that were best suited to address a particular set of problems. The ultimate goal of the planning exercise was to address as many of the physics problems as possible at existing facilities and to identify the engineering issues. The ultimate goal is a technical design report (TDR) for an energy frontier collider based on one of these advanced accelerator concepts by 2035. It was recognized that demonstrating an interim "near-term" application of the leading concept was important for proving the validity, technical readiness and usefulness of the scheme and for generating the considerable resources needed to build a prototype accelerator.

In response to this report, the PWFA collaboration has come up with an initial, five-year R&D plan for FACET-II that is consistent with the DOE-HEP strategic plan. As mentioned earlier, the decadal goal of this plan is to demonstrate (as much as the FACET II facility allows) electron beam parameters expected from a single stage of a future multi-stage PWFA-based linear collider (PWFA-LC). It should be noted that the design of a PWFA-LC itself is a multi-parameter problem. Optimization of the design must take into account the limitations on some of these parameters that will only be revealed by experiments. We have broken up the decadal goal of this program into several smaller goals with the intention that all these goals can be simultaneously achieved in a single integrated demonstration within the decade. We first list the five-year goals and then discuss them one by one.

The first goal is to show that the 10 GeV drive bunch can be substantially depleted of its energy to provide a drive beam to wake energy transfer efficiency >80%. The second goal is to demonstrate that the trailing bunch can gain at least 10 GeV energy in less than 1 meter from a single stage of PWFA. The third goal is to show that this 10 GeV energy gain can be obtained while extracting 50% of the energy stored in the wake, i.e., a net drive bunch to the trailing bunch energy transfer efficiency of 40%. A fourth goal is to show that the trailing bunch energy spread can be kept below 2%. A fifth goal is demonstrate the emittance preservation of a low emittance trailing beam as it gains 10 GeV in a single stage. If emittance growth occurs, then the goal is to identify the various factors causing growth (e.g. beam mismatch, incomplete blow out, transverse instabilities, ion motion etc.) and design mitigating strategies.

3. Day 2: Collaborative Effort to Understand Transverse Wakes Under Strong Beam Loading

3.1 Tolerances and transverse wake excitation under strong beam loading

The experimental program outlined in 2.3 is ambitious and important. It depends on the hardware and expertise developed within the plasma wakefield accelerator collaboration over the last two decades. When successful, a demonstration of emittance preservation under strong beam loading will engender a whole new set of questions regarding tolerances to beam imperfections and relative beam alignment. The PWFA community was excited by the prospect of such an experiment and the collaborations are expanding.

To refine the models for future colliders based on plasma wakefield acceleration [7], the transverse wakefield amplitude needs to be quantified more precisely. The measurements will require the development of new techniques for creating the relevant beam parameters and offsets. Lessons learned from FACET were reviewed by Adli. They have so far indicated that although betatron oscillations can be excited and measured, the hosing instability from transverse wakes has not been observed. New single shot diagnostics will also be needed to characterize the beam before and after the plasma. Simultaneously measuring the transverse centroids along both the drive and witness beams with femtosecond precision on a single shot basis, will require the development of new diagnostics. Ideas such as a quadrant electro-optical sampling system were discussed. The usable range of the existing so-called butterfly emittance measurement was deemed sufficient for experiments with micron level emittance. Ultra-high brightness beams will require alternate techniques such as spectrally resolved betatron radiation. Over the first two days, the discussion progressed from absolute statements that 'emittance preservation will not be possible' to more nuanced quantitative predictions for performance.

3.2 Towards a theoretical model

The experimental program described above will provide a solid foundation for theoretical models of the transverse wakefields in a plasma wakefield accelerator. A well tested theoretical basis will allow improved PWFA-LC designs by filing the gaps between those regions accessible with experiments and what is possible to simulate. The UCLA and Tsinghua University groups have developed a theoretical basis for non-linear plasma wakefields that has been tested against experiments at FACET. These theories successfully predicted the longitudinal behavior under strong beam loading (efficiency, energy spread). These groups have also developed theoretical models for the hosing growth rate that correctly predicted the lack of hosing in FACET experiments.

These groups also presented early results from an alternate approach to describing the wakefields as a series of modes. An FNAL group has used accelerator formalisms that treat the plasma cavity as a traditional but high frequency accelerator. In these models, the growth rates for transverse wakefields vs energy spread and beam loading are more severe than the plasma approach predicts. Stupakov from SLAC has developed a hybrid Green's function approach with predictions in between the UCLA and FNAL models. The community has come together to address the issues of beam quality under strong beam loading. This is an important step on the HEP 10 year R&D Roadmap for plasma wakefield acceleration [10] and a critical component of the FACET-II experimental program.

3.3 Alternate Regimes

Many high energy physicists think that the next frontier energy collider for HEP research should be an electron positron collider such as the ILC or CLIC. For plasma wakefield accelerators to fill this role, there needs to be a credible scenario to accelerate positrons to high energy with sufficient intensity. FACET and FACET-II are the only facilities in the world that can study this physics. Progress from continued analysis of FACET data was reviewed including recent publications of two-bunch positron PWFA (relevant for afterburner configurations) [11] and the measurement of the transverse wakefields in a hollow channel plasma accelerator [12].

Similarities and differences with cylindrical dielectric structures were explored in talks on dielectric wakefield acceleration. Recent experiments at FACET observed metallization of silicon dioxide at high fields, potentially limiting the maximum usable gradient. The discussions included analysis of how to suppress beam breakup (FNAL/ANL).

On the topic of positron PWFA, recent experimental work at FACET performed the first studies of positron acceleration in both the non-linear and quasi-linear regimes [11]. Models for hosing saturation in the quasi-nonlinear regime again suggested that the sensitivity to hosing may be less severe as ever more realistic effects are included in the models [13].

New directions for positron acceleration were proposed using the second FACET-II beamline in sector 20, the so-called sailboat chicane, to provide electron driven wakefields. An alternative proposal to Gaussian drive beams was exotic hollow-driver beam shapes, e.g. the so-called non-neutral fireball, tailored to control the shape of the wakefields.

This session highlighted the need for continued progress on all three fronts – theoretical, numerical and experimental to identify an optimal regime for positron plasma wakefield acceleration.

4. Day 3: Injection Techniques and Ion Motion

4.1 Generating High Brightness Beams at FACET & FACET-II

Applications of plasma wakefield accelerators (PWFA) to colliders and Free Electron Lasers (FELs) require the generation of high brightness electron beams. The Advanced Accelerator Development Strategy Report, which was published by the DOE Office of Science in 2016 [10] recognized this as one of the primary challenges for the PWFA community over the next decade. To address this challenge, schemes have been developed for injecting plasma electrons into the wakefield to generate very low emittance electron bunches ($<\sim$ 1mm-mrad). Several of these methods were experimentally tested during the operation of FACET [14, 15, 16], while several other methods [17, 18, 19, 20] have shown great potential in simulations. As we look towards FACET II, it will be crucial to further explore the relative merits of these injection methods and to identify the ones that can reliably provide robust beams with a high quality that is suitable for collider/FEL applications.

Over the last decade, the PWFA community has invested significant efforts to explore methods for injecting the electrons from the plasma itself into the wakefield, thus generating a bunch with very low emittance. These techniques can be broadly divided into two categories: methods based on ionization injection, and methods based on the self-injection of electrons from the boundaries of the accelerating cavity. Briefly, in ionization injection methods, the electron beam is generated by further ionizing an impurity within the accelerating field of the wakefield. As these electrons are released within the accelerating field, they can gain enough energy to keep up with the travelling plasma wave and form an accelerating bunch. In contrast, self-injection occurs through perturbing the trajectory of the plasma electrons that have formed the accelerating cavity. Ordinarily, these electrons stream in a spherical boundary layer around the accelerating region, which is devoid of electrons. It has been shown, however, that if the trajectory of these electrons is perturbed, such as by rapidly reducing the plasma density, they can be injected into the acceleration cavity, where they may form an electron bunch with very low emittance. Both categories of electron injection were explored at FACET in proof-of-principle experiments that yielded very encouraging results. In all of these experiments, the high current electron beam generated by the FACET linac was used to drive the plasma wakefield.

With regards to ionization injection, two experimental groups demonstrated acceleration of electron bunches with an emittance on the order of 1 mm-mrad [14, 15]. This was an important demonstration, because these emittance values are competitive with those generated by a photocathode. The principle distinction between the two experiments was the method of ionization. In the first experiment [14], the field of the high current FACET beam itself initiated the ionization of the electrons that formed the accelerating bunch while in the other [15], an external source (a laser pulse) was used for the same purpose. Thus, the second experiment was much more complex than the first, requiring sophisticated diagnostics to enable the alignment of the FACET driver and the ionizing laser in time and space. On the other hand, the additional diagnostics enabled independent control over the timing between the injector (laser) and the driver (FACET beam), which resulted in discovery of several distinct regimes of interaction, each producing electron bunches with distinct properties that may be suitable for different applications [15, 16].

Progress was also made at FACET towards the characterization of electrons produced through self-injection of plasma electrons using a sharply decreasing density profile (or a density down ramp). The challenge in these experiments is to produce the needed plasma density profile, which requires a down ramp with a characteristic length on the order of a few hundred microns followed by a plasma region with a plateau density profile. An experiment towards this goal was carried out by the same group that conducted the laser ignited ionization injection experiment described above [15]. The sharp density down ramp naturally emerged in the regime where the laser arrived much earlier than the FACET beam. These experiments resulted in injected electron bunches with similar emittance to those created by ionization injection, i.e. on the order of 1 mm-mrad [16]. However, the simulations have shown that with proper control over the scale of the density down ramp, it is possible to achieve emittance values below 0.1 mm-mrad [17].

In FACET-II, it will be important to continue to explore and optimize these injection schemes. Each scheme has its own relative merits and strengths and will yield a beam with different properties that may be suitable for different applications. The ionization injection scheme initiated by the drive beam is experimentally simple and robust, needs a relatively low current beam (~20-30 kA), and demands no constraints on the transverse beam size. Optimizing this scheme may yield a relatively low emittance (<1 mm-mrad). The laser-assisted ionization injection is experimentally more complex, but the independent control of the injection laser and the driver creates the possibility of generating a beam with even smaller emittance than the first scheme. Finally, the self-injection scheme is in principle very robust and has the potential of generating the smallest beam emittance, but generating the required plasma density profile, including a down ramp with the necessary scale length (<200 μm) requires research and development. With a wide variability in complexity, risk, and potentially transformative results, all of these schemes are compelling candidates for exploration in FACET II. It will be important to pursue all of them in order to assess and judge their experimental potential.

4.2 Off-ramp applications

The Office of High Energy Physics Advanced Accelerator Research Strategy Report [10] roadmap for plasma wakefield accelerators calls for developing off-ramp applications and concepts for a demonstration facility en route to a collider. A SLAC task force has been developing concepts for such a facility and their progress was presented along with plans for a white paper to be completed in 2018. The availability of ultra-high brightness beams from plasma accelerator-based injectors may open new avenues for future light sources. An early career award recipient at LBNL presented the status of work developing a VUV FEL based on laser wakefield acceleration. A common theme was that all of these techniques require experimental demonstrations of the predicted beam qualities to inform facility designs.

4.3 Increasing international competition & interest

The success of FACET has attracted international interest and new competition in the area of beam driven plasma acceleration. DESY presented plans for a recently started wide-ranging effort to develop novel accelerator technology. FLASHForward is a next-generation experiment for beam-driven plasma accelerator research consisting of a dedicated beamline and experimental area. The presentation highlighted many similarities to FACET & FACET-II and made it clear that they are learning from the successes of FACET. The facility includes GeV beams, differential pumping systems, an X-band transverse deflecting cavity, a terawatt experimental laser and a notch collimator system for tailoring single and double bunch profiles.

Beamline commissioning started in August 2017 and they have commissioned the beamline to the end of the final focus. The majority of experiments aim to focus on key challenges of photon science and particle physics applications of plasma wakefield acceleration (PWFA). The first plasma experiments are planned for early 2018 and will focus on beam quality and mitigation of the hosing instability. Next generation experiments will focus on plasma injectors as sources of ultra-high brightness beams.

The LUX facility at DESY is built around a 200TW laser that has been designed with an accelerator quality control system for reliability and stability. The primary research focus is on high repetition rate plasma targets and compact undulators for radiation characterization from laser wakefield acceleration produced beams.

The SINBAD facility, part of the Athena research program, will use S and X-band linac components to generate beams for PWFA research. The facility is under construction in an existing accelerator enclosure. They plan to study externally injected beams using low density, low gradient plasma acceleration.

4.4 Ion motion

Almost a decade ago it was proposed that when, in a plasma wakefield accelerator, the ratio of the peak beam density to the background plasma density exceeds the ion to electron mass ratio ($n_p/n_0 \geq m_i/m_e$), the plasma ions would move within the transit time of beam, alter the linear focusing of the ion column and seriously degrade the beam emittance [21]. For PWFA based linear colliders with very dense beams, large emittance growth would be unacceptable. Results were presented from subsequent numerical investigations that have studied the effects in greater detail [22]. The studies revealed new dynamics indicating a saturation of the emittance growth with reduced, and potentially acceptable levels of, emittance growth. Mitigation strategies were also discussed.

Another presentation showed that alteration of the transverse focusing from even small amounts of ion motion would lead to subtle but non-negligible distortion to the accelerating wakefield. In the non-linear blow out regime, the accelerating field would otherwise have no radial dependence. However, the Panofsky-Wenzel theorem connects the ion motion-induced deviation of the transverse focusing fields to changes in the radial dependence of the accelerating fields. This would cause a subsequent growth in the uncorrelated energy spread of the beam. The resulting uncorrelated energy spread was estimated for various beam parameters and the implications for FEL applications were discussed.

5. Day 4: Simulations & New Directions

5.1 Summary of computational challenges and needs

At the Friday morning session, there were several talks on simulation software and codes that could be of use for modeling the experiments at FACET-II. This software included QuickPIC, OSIRIS, Warp-X, and VSIM. The software talks addressed the need to model near term experiments as well as the need to model parameters of relevance to a future collider that are beyond the capability of the experiments. The talks also included material related to specific challenges for modeling plasma-based acceleration, beam loading, synchronized injection, staging, hosing, dielectric wakefield acceleration, disruption, and QED. The talks also covered best practices and the need to make the software easy to use.

In the first talk, "Status and future plans for open source QuickPIC", W. An described the software engineering for the open source version of QuickPIC. He mentioned that there were plans for a workshop on QuickPIC in the first half of 2018. QuickPIC remains the workhorse for designing plasma wakefield acceleration experiments at FACET-II. In the second talk, "OSIRIS: Tool for modeling plasma-based acceleration issues", W.B. Mori covered the diverse topics that OSIRIS has been used to study including PWFA at SLAC since the late 1990s. In this talk, it was mentioned that modeling near term plasma-based acceleration experiments at FACET-II does not require exascale resources; however, modeling parameters of relevance to a linear collider will require such resources. He also mentioned that the first annual OSIRIS Workshop was held in September 2017 and over 60 people attended. OSIRIS which is now used by more than 100 people worldwide has been rewritten into version 4.0 (to make it easier for co-development) which is available as open access through an MoU. New field solvers (which mitigate the numerical Cerenkov Instability), simulations of disruption and the QED package were mentioned (a longer talk on the QED package was given by T. Grismayer later in the afternoon). He also described results on synchronized injection using both the full 3D and quasi-3D algorithms, indicating that plasma-based acceleration could produce unique electron beams that could drive a future XFEL. Issues and plans for improving the dynamic load balancing routines were discussed.

J. L. Vey gave a talk on, "Warp-X: a new exascale compute platform for beam-plasma simulations". Warp-X is a new code being developed with the goal to include adaptive mesh refinement as well as higher order or pseudo spectral (FFT based) field solvers together with high performance. Preliminary results on test problems were presented. The ability to carry out simulations in a Lorentz boosted frame is also simultaneously being addressed. The goal is to provide the capability to carry out start to end simulations of 10-100 plasma based accelerator stages. Warp-X will be open source.

J. R. Cary gave a presentation on, "VSim/Vorpal updates: Ease and performance", in which he described the customer base, activities to make VSim easy to use, applications of VSim, and progress on improving the performance of VSim. He emphasized that the customer base in photonics does not necessarily need high performance and this base is a major driver for ease of use and setup. Areas where performance is being addressed include adding variable meshes and ensuring that algorithms can run on GPUs and many-core (but not necessarily fully optimized). VSim was used for modeling injection experiments at FACET and for designing experiments on injection on FACET-II.

D. Bruwhiler gave a talk on, "8 years of beam-driven wakefield simulation-lessons learned, reduced models, and future plans" in which he described his experiences in simulation schemes which included both lasers and particle beams. While r-z codes work for particle beams they do not work for lasers (the quasi-3D scheme permits modeling lasers with r-z like codes). He described how 2D slab is problematic due to geometrical effects for both the laser and wakefield and how they used hybrid approaches where the laser was modeled as prescribed fields or only for a short time. He mentioned that low resolution 3D is preferred to high resolution 2D slab. Once the electrons are injected then they can be read into another code which pushes them in prescribed wakefields or in wakefields produced by a particle beam.

5.2 New directions: High Field QED Studies

Proposals for High field QED experiments are often dismissed based on a sentiment best characterized by Schwinger: "An experiment will not be believed if it will show a different result from a theoretical prediction". At FACET-II, we do not disagree with this assessment for $\chi \gtrsim 1$, where χ is Lorentz invariant parameter $\chi = E^{*}/E_{cr}$, which compares the electric field in the electron/positron rest frame E^{*} with the QED critical field $E_{cr} = \frac{m^2c^2}{e\hbar} = 1.32 \times 10^{18}\ V/m$. The regime $\chi \gtrsim 1$ is explorable by combining highly energetic particles with strong electromagnetic fields, an experimental scheme first realized in the SLAC E-144 experiment. In the near future, 10PW-class laser facilities will continue to explore new physical phenomena at the intensity frontier, e.g., QED cascades.

However, lasers are not the only tool to study strong-field QED. Notable alternatives are highly charged ion beams, strong crystalline fields and very dense electron/positron beams. The fields of the FACET-II beams, for example, are equivalent to PW lasers and at the verge of reaching the regime $\chi \gtrsim 1$, where the recoil of individual photons (quantum radiation reaction) and the creation of matter from pure light become important and eventually dominate the interaction of light and matter completely.

Colliders intended to explore the energy frontier like ILC or CLIC are designed to mitigate strong fields by colliding flat and elongated beams. On the contrary, we consider maximizing the beam-beam forces. By extrapolating the FACET-II design to highly compressed and tightly focused 100 GeV colliding beams, we expect to access the regime of $\alpha\chi^{2/3} \gtrsim 1$ (i.e., $\chi \gtrsim 10^3$; $\alpha \simeq 1/137$ denotes the fine-structure constant), where the commonly applied loop expansion of strong-field QED is conjectured to break down and the theory becomes fully nonperturbative.

In this regime, the mass $\mu = (m_e\alpha\chi^{2/3})^{1/2}$ acquired by the photon from the electromagnetic background field via quantum fluctuations is of the same order as the electron/positron mass induced by the Higgs mechanism, implying that essential properties of the theory are substantially changed and that a qualitatively new regime of light-matter interaction is reached.

The fundamental challenge in realizing such strong fields is the radiative energy loss by charged particles during the field transition region. Therefore, the regime $\chi \gg 1$ is only accessible if the switching time of the background field is smaller than the electron/positron radiative lifetime. Beam-beam collisions – unlike strong optical laser pulses – have the potential to fulfill this challenging requirement.

In light of the fact that the Large Hadron Collider (LHC) has so far not discovered new physics at the energy frontier, it is time to consider alternative possibilities to challenge our knowledge of the fundamental laws of nature. We are assessing the technical feasibility of a 100 GeV-class particle collider, capable of generating electromagnetic fields which exceed the QED critical field by several orders of magnitude. Such a device would enable us to test our understanding of the universe under unprecedented extreme conditions at the intensity frontier.

Notably, all existing theoretical calculations break down in this regime, implying that the experimental forefront envisaged here has the potential to establish a new research field and to stimulate the development of a new theoretical methodology. The lack of a thorough theoretical understanding of this novel regime represents a potential caveat to the analysis. These circumstances, however, render its experimental exploration even more attractive and desirable.

An experimental program was discussed for the $\chi \gtrsim 1$ regime HF QED, studies of the quantum Beamstrahlung (for the first time). There are also existing simulation codes that can be benchmarked at FACET-II to help develop the science case for a facility to study fully non-perturbative QED accessing $\alpha\chi^{2/3} \gtrsim 1$.

5.3 Facility Improvements and Upgrades

Many of the envisioned FACET-II PWFA programs will benefit from improved energy and stability in the FACET experimental laser system. A presentation by Alan Fry from the LCLS laser group discussed how the FACET-II ionization laser system could be upgraded, at moderate cost, to achieve >25TW peak power at 5Hz repetition rate. Techniques for realizing better laser beam quality and stability at the experimental area were also discussed including spectral phase control, a higher energy pump laser, improved beam transport optics and improved diagnostics.

New directions such as high field QED studies, such as discussed in Section 5.2, requiring 100TW or more peak power, will require a more significant investment. A 100TW class upgrade for nonlinear QED is possible at higher cost with multiple upgrades throughout the laser, beam transport, and delivery systems. Design and operations support could be provided by the experienced LCLS Laser Science & Technology Division that currently supports the existing FACET (and FACET-II) experimental laser.

The addition of a second beamline in S20 to allow simultaneous delivery of e- & e+ bunches to the IP would enable exotic states suitable to study certain astrophysical processes. Relativistic beam-plasmas can support a wide range of instabilities which are relevant for astrophysical environments, but their long-term evolution is not well understood. FACET-II experiments can probe for the first time some of these processes: e.g. competition between the oblique, Weibel, and Bell instability. PIC simulations presented illustrate the ability to excite and probe these instabilities for idealized FACET-II parameters. More detailed studies are needed to address exact experimental conditions and identify the most appropriate diagnostics.

Material studies with compressed electron & positron beams were also discussed. The electro-magnetic field of the FACET-II beams has unique and attractive properties for exciting materials: large amplitude, DC, and short duration. One area of interest would build on studies at the FFTB and FACET facilities and use the intense FACET-II beams as a magnetic probe of spin memory to test the temporal limit of switching and the role of the atom lattice in trapping. The strong 100 fs field impulse is well coupled to 10's of μm metal-insulator-metal devices and the would also act as a mechanical-electric probe of resistive memory with a time scale ~ atomic motion. The two bunch capability afforded by the additional beamline would enable pump-probe and field reversal studies never before possible.

Appendix A: Workshop Agenda

Table 1: Agenda for the 2017 FACET-II Science Workshop

Start Time	Session Topic	Presentation	Presenter	Affiliation
		Tuesday		
09:00 am	Overview	**Workshop Introduction**	Mark Hogan	SLAC
09:15 am	Overview	**FACET-II Project Update**	Vitaly Yakimenko	SLAC
09:45 am	Overview	**FACET-II Capabilities: e-, e+, two-bunches, sailboat: extreme peak current, non-neutral fireballs etc**	Glen White	SLAC
10:30 am		**Coffee Break**		
11:00 am	Overview	**High Level Summary of Anticipated Experimental Program @ FACET-II**	Mark Hogan	SLAC
11:30 am	Emittance preservation & pump depletion	**Energy doubling with emittance preservation and pump depletion**	Chan Joshi	UCLA
12:15 pm		**Lunch**		
01:15 pm	Emittance preservation & pump depletion	**Plasma sources with density ramps (Li oven + apertured controlled gas pressure)**	Ken Marsh	UCLA
01:45 pm	Emittance preservation & pump depletion	**Differential pumping: IP integration & performance**	Christine Clarke	SLAC
02:15 pm	Emittance preservation & pump depletion	**Plasma source with optically generated density ramps**	Mike Litos	UC Boulder
02:45 pm	Emittance preservation & pump depletion	**Emittance measurements: Butterfly technique and implications for spectrometer**	Brendan O'Shea	SLAC
03:15 pm		**Coffee Break**		
03:30 pm	Emittance preservation & pump depletion	**FACET-II diagnostics overview**	Nate Lipkovitz	SLAC
04:00 pm	Emittance preservation & pump depletion	**Novel diagnostics and beam phase space recovery**	Claudio Emma	SLAC

04:30 pm	Emittance preservation & pump depletion	**Expected beam performance with stability analysis**	Glen White	SLAC
05:00 pm	Emittance preservation & pump depletion	**Benefits of a zig-zag compression design for FACET-II**	Yichao Jing	BNL
05:30 pm	Emittance preservation & pump depletion	Discussion		
06:00 pm		**Adjourn**		
		Wednesday		
09:00 am	Transverse Wakefields with strong beam loading	**Emittance vs Loading (introduction, theory with high level simulation results)**	Sergei Nageitsev	FNAL
09:30 am	Transverse Wakefields with strong beam loading	**Theoretical progress (multi-modal analysis)**	Xinlu Xu	UCLA/SLAC
10:00 am	Transverse Wakefields with strong beam loading	**Detailed computational discussion and next steps in understanding emittance vs. loading in PWFA**	Weiming An	UCLA
10:30 am		**Coffee Break**		
11:00 am	Transverse Wakefields with strong beam loading	**Lessons learned from FACET and path forward for FACET-II experiment (offset knobs & what we will see on spectrometer)**	Erik Adli	U. Oslo
11:30 am	Transverse Wakefields with strong beam loading	**Diagnostic requirements for witness bunch offsets (r,z)**	Mike Litos	UC Boulder
12:00 pm	Transverse Wakefields with strong beam loading	**Calculation of wakefields for plasma-wakefield accelerators**	Gennady Stupakov	SLAC
12:30 pm		**Lunch**		
01:30 pm	Positrons, hollow channels and dielectrics	**Hollow channel longitudinal & transverse wakes**	Carl Andreas Lindstrom	University of Oslo
02:00 pm	Positrons, hollow channels and dielectrics	**Dielectric Wakefield Accelerators: status & what's next**	Gerard Andonian	UCLA
02:30 pm	Positrons, hollow channels and dielectrics	**Analysis of BBU in compact structure-based wakefield accelerators and a suppression method**	Stanislav Baturin	University of Chicago

03:00 pm	Positrons, hollow channels and dielectrics	**Saturation of the beam-hosing instability in quasi-linear plasma-wakefield accelerators**	Remi Lehe	LBNL
03:30 pm		**Coffee Break**		
03:45 pm	Positrons, hollow channels and dielectrics	**Positron PWFA - what we've learned and what's next**	Sebastien Corde	Ecole Polytechnique
04:15 pm	Positrons, hollow channels and dielectrics	**Electron Driven Positron Acceleration with the Sailboat Chicane**	Weiming An	UCLA
04:45 pm	Positrons, hollow channels and dielectrics	**Non-neutral fireball and possibilities for accelerating positrons with plasma**	Jorge Viera	IST
05:15 pm	Positrons, hollow channels and dielectrics	**Discussion**		
06:00 pm		**Adjourn**		
		Thursday		
09:00 am	Injection experiments	**Ionization injection - what we've learned and next steps**	Navid Vafaei	Stonybrook University
09:30 am	Injection experiments	**Density Downramp Injection - Prospects for Ultra-high Brightness Beams**	Xinlu Xu	UCLA/SLAC
10:00 am	Injection experiments	**Trojan Horse and Plasma Torch Injection - lessons learned and next steps**	Bernhard Hidding	University of Strathclyde
10:30 am		**Coffee Break**		
11:00 am	Injection experiments	**Plans @ DESY**	Jens Osterhoff	DESY
11:30 am	Injection experiments	**Low emittance measurements:100nm from betatron spectrum**	Nathan Majernik	UCLA
12:00 pm	Plasma Accelerator based FELs	**Status of task force efforts**	Mark Hogan	SLAC
12:30 pm		**Lunch**		
01:30 pm	Plasma Accelerator based FELs	**Realizing an FEL from a Plasma Accelerator - Progress and Plans at LBNL**	Jeroen VanTillborg	LBNL
02:00 pm	Ion Motion	**Ion motion effects on emittance**	Weiming An	UCLA

02:30 pm	Ion Motion	**Ion motion effects on energy spread**	Xinlu Xu	UCLA/SLAC
03:00 pm		**Coffee Break**		
03:15 pm	Ion Motion	**Emittance preservation in plasma-based accelerators with ion motion**	Carlo Benedetti	LBNL
03:45 pm	Ion Motion	**Long term wake evolution: heating & ion wakes**	Jorge Viera	IST
04:15 pm	Ion Motion	**Imaging of beam-induced plasma structures: FACET and FACET-II**	Mike Downer	UT Austin
04:45 pm	Ion Motion	**TeV/m in Plasmas**	James Rosenzweig	UCLA
05:15 pm	Ion Motion	**Discussions**		
05:30 pm		**Adjourn**		
06:00 pm		**Wine & Cheese Reception – Building 52 Lobby**		
		Friday		
09:00 am	Simulation Codes	**QuickPIC**	Weiming An	UCLA
09:30 am	Simulation Codes	**OSIRIS**	Warren Mori	UCLA
10:00 am	Simulation Codes	**WarpX & Exascale**	Jean LucVay	LBNL
10:30 am		**Coffee Break**		
11:00 am	Simulation Codes	**VSIM**	John Cary	UC Boulder & TechX
11:30 am	Simulation Codes	**8 Years of Beam-Driven Wakefield Simulation -- lessons learned, reduced models, and future plans**	David Bruhwiler	Radiasoft
12:00 pm	New Directions @ FACET-II	**Active plasma lenses – limitations on beam energy/density and aberrations**	Jan-Hendrik Röckeman	DESY
12:30 pm		**Lunch**		
01:30 pm	New Directions @ FACET-II	**High Field QED enabled by 100TW + 15GeV**	David Reis	SLAC
02:00 pm	New Directions @ FACET-II	**High Fields: compressed 10GeV+300MeV—> 100GeV/100GeV**	Sebastian Meuren	Princeton University

02:30 pm	New Directions @ FACET-II	**High Fields: computational challenges**	Thomas Grismayer	IST
03:00 pm		**Coffee Break**		
03:15 pm	New Directions @ FACET-II	**Laser upgrade options: >100TW, transport and quality improvement**	Alan Fry	SLAC
03:45 pm	New Directions @ FACET-II	**Laboratory Astrophysics studies with electron-positron beams at FACET-II**	Frederico Fiuza	SLAC
04:15 pm	New Directions @ FACET-II	**Material studies with compressed electron & positron beams at FACET-II**	Ioan Tudosa	University of Pennsylvania
04:45 pm	New Directions @ FACET-II	Discussions		
05:15 pm		**Adjourn**		

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