FACET-II Science Workshop Summary Report

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1. Summary

The second in a series of FACET-II Science Workshops was held at SLAC National Accelerator Laboratory on October 17-19, 2016 [1]. The workshop drew thirty-five participants from eighteen different institutions including CERN, DESY, Ecole Polytechnique, FNAL, JAI, LBNL, LLNL, Radiabeam, Radasoft, SLAC, Stony Brook, Strathclyde, Tech-X, Tsinghua, UC Boulder, UCLA and UT Austin. 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. All presentations are linked to the workshop website as a permanent record.

Day 1 of the workshop provided an overview of FACET-II, discussions of high-level PWFA research priorities and options for plasma sources. Discussions quickly focused on the design and QuickPIC simulation of a potential first experiment. The idea illustrated key science deliverables: pump depletion of the drive beam, high efficiency & low energy spread acceleration of the witness beam, beam matching with tailored plasma sources, and emittance preservation of the accelerated witness beam. The proposed experiment also illustrated key upgrades from FACET to FACET-II that are required to allow such ambitious goals: the low emittance photoinjector beams, a plasma source with optimized density ramps, and differential pumping systems to eliminate beam scattering from vacuum windows. The infrastructure for generating two bunches developed at FACET will be available at FACET-II and in addition the photoinjector will allow even better performance. Simulations of the injector have already converged on a set of beam parameters that satisfy experimental needs. After just the first day, it was clear the FACET user community is coming together on this high priority goal. Looking ahead, new collaborations are already forming to study the next phase of this experiment – mitigation of beam breakup with strong beam loading.

Plasma sources are an enabling technology for many FACET-II experiments. They are the accelerating structure and by far the strongest focusing elements in the beamline. Sources based on the lithium vapor heat pipe ovens developed for the last eighteen years of experiments at SLAC will need more precise control of the temperature (vapor density) profile to tailor density ramps for emittance preservation. Laser ionized gas sources will play an important role for experiments on high brightness beam generation and positron acceleration. Plasma lenses have recently been used on low energy beams, but there are practical limitations when applying this technology for FACET-II beams. Discussions of these limitations included: aberrations from non-linear current, scaling to 10GeV, and operation with high density beams.

TeV/m gradients will be accessible with the highly compressed photoinjector beams at FACET-II. This regime is likely not an avenue for collider applications, but such extreme fields could open exciting avenues of research in other fields. It may also be a route to a first application with the generation of coherent x-ray radiation.

Plasma imaging at FACET has already enabled new physics studies such as the phenomenon of head erosion in PWFA. The plasma has many roles: laser waveguide, electron source, and accelerator. In addition, the structure is dynamic and evolving. Proposed plasma imaging upgrades for FACET-II will allow experimenters to ‘see’ this evolution shot-to-shot.

Day 2 of the workshop focused on Witness Injectors (Staging Studies) & Diagnostics. A low energy (300MeV) witness bunch injector concept is compatible with the FACET-II design. This is a possible implementation for staging studies and high transformer ratio experiments. Future work will investigate how to increase the peak current of the beam to maximize the physics return of such an investment. Options for upgrading the FACET Ti:Sapph laser were discussed. Improvements in laser beam quality are more important than the total delivered energy. Many useful diagnostics developed at FACET will be used in FACET-II. One recurring recommendation was that FACET-II should avoid beam windows downstream of the plasma, especially for experiments with low emittance beams.

Day 3 of the workshop continued discussions on low emittance beams and then focused on computational tools for FACET-II and future linear collider designs. Computation has been an essential component of FACET science. Experiments at the FFTB and FACET enjoyed a strong connection between theory, computation and experiment – every major result benefited from strong collaborations. Existing codes are capable of supporting the key elements of the FACET-II PWFA program. In addition, the Exascale project is developing a code that can effectively benefit from new hardware and simulate both classes of driver. This new development will support detailed collider designs.

The FACET-II user community is developing a consensus on the first experiments. Responsibilities for different groups have been identified and will continue to be coordinated through collaboration meetings and future FACET-II workshops. The next FACET-II Science Workshop will be in the fall of 2017 and will again concentrate on high level research directions. After the FACET-II project has been baselined, there will be a call for proposals. In 2018, the FACET/FACET-II external advisory committee, SAREC, is expected to review first proposals for beam time in 2019.

2. FACET-II Overview

2.1 Welcome and why we are here, define charge for each session M.J. Hogan, SLAC

The 2016 FACET-II Science Workshop was the second 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 define 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 were then introduced following the agenda given in Table 1.

Table 1: Agenda for the 2016 FACET-II Science Workshop

Session	Topic	Speaker	Institution
Monday 10/17/2016			
FACET-II Overview	Welcome and why we are here, define charge for each session	Mark Hogan	SLAC
	FACET-II Status	Vitaly Yakimenko	SLAC
	FACET-II Design	Glen White	SLAC
Coffee Break			
Plasma Sources	Overview of requirements for Plasma Sources based on experimental needs	Chan Joshi	UCLA
	Heat pipe ovens	Ken Marsh	UCLA
Lunch			
Plasma Sources	Laser ionized gas	Mike Litos	U.C. Boulder
	Hollow channel overview and prospects	Spencer Gessner	CERN
	Steady-state, free-flow plasma targets	Jens Osterhoff	DESY
Coffee Break			
Plasma Sources	Active plasma lenses at 10GeV	Jeroen van Tilborg	LBNL
	TeV/m	Jamie Rosenzweig	UCLA
	Plasma diagnostics	Rafal, Mike Downer	U.T. Austin
Discussion		All	
Adjourn			

	Tuesday 10/18/2016		
Witness Injector	Requirements: lpk, emittance, alignment, beam size, charge	Mark Hogan	SLAC
	Zig zag and peak current optimization	Vladimir Litvinenko	Stonybrook
Coffee Break			
	4 GeV option	Joe Frisch	SLAC
	LWFA probe beam & witness injector option	Wei Lu	Tsinghua
Lunch			
Diagnostics	EOS optimization	E210	E210
	Hybrid linac-laser-plasma diagnostics and kicker	Bernhard Hidding	University of Strathclyde
	Energy Spectrometer & TCAV?	Brendan O'Shea	SLAC
Coffee Break			
Diagnostics	FACET experience & interference tech.	Nate Lipkowitz	SLAC
	E200/E225 quad scan experience	Sebastien Corde	Ecole Polytechnique
	E-210/E-217 experience (butterfly)	Carl Lindstrom	Oslo
	Prospects for crystal channels	Brendan O'Shea	SLAC
Discussion			
Adjourn			
	Wednesday 10/19/2016		
Low Emittance Diagnostics	E200 betatron radiation experience	Sebastien Corde	Ecole Polytechnique
	Gamma spectrometer	Fellicie Albert	LLNL
	Betatron radiation in wakeless regime	Jamie Rosenzweig	UCLA
Coffee Break			
Computation	Needs and challenges for modeling FACET-II and Beyond	Warren Mori	UCLA
	Benefits of the Exascale ECP and CAMPA programs to the modeling of PWFA	Jean-Luc Vay	LBNL
	Current status and near term needs for modeling FACET-II	Weiming An	UCLA
Adjourn			

2.2 FACET-II Status

V. Yakimenko, SLAC

FACET-II will be a National User Facility and is being planned as a community resource delivering high energy, high peak current beams of electrons and positrons to a diverse user community. At the time of the workshop, the FACET-II Project had recently completed a successful CD2/3A review and was awaiting approval from the DOE ESAAB. The FACET-II Project will be executed in stages. Stage 1 will deliver high energy, high peak current, low emittance electron beams from an LCLS-II style

photoinjector beginning Q4 of FY19. Stage 2 will restore the capability to deliver high energy, high peak current positron beams from a hybrid system combining the SLC/PEP-II/FACET positron source with a new state of the art damping ring constructed in sector 10 of the SLAC linac tunnel. The Project is planned to accommodate an additional capability, the so-called sailboat chicane, that will allow simultaneous delivery of electrons and positrons to the experimental area. This capability is on the contingency buy-back list for the FACET-II Project and the user community has been encouraged to begin thinking of how best to exploit such a unique capability.

2.3 FACET-II Design **G. White, SLAC**

The FACET-II design takes into account the experience gained in operating FACET. FACET represented a beam dynamics challenge with simultaneous transverse and longitudinal phase space requirements as well as additional user-driven flexibility requirements. FACET-II Threshold and Objective Key Performance Parameters (KPP) were reviewed. Once these parameters are achieved, FACET-II can transition to operations and begin tailoring beams for individual experiments.

The FACET-II electron injector is based on the currently operating LCLS injector in sector 20. Simulations indicate that all KPPs can be met and peak parameters benefit from the increased transverse and longitudinal brightness of the photoinjector compared to the FACET thermionic injector and damping ring beam. The compression design satisfies the KPP's and has the flexibility to satisfy all planned experimental activities as verified with tracking simulations. The pulse format required to produce positrons and the bunch compression required to produce high peak currents have also been verified with tracking simulations.

A Monte Carlo simulation including all known error sources was performed. It concluded that the KPP Design parameters are met with expected error tolerances. As an example, the two bunch configuration requested by the E200 collaboration was verified in simulations.

The high-brightness photo injector source at FACET-II can provide compressed electron bunches to Sector 20 with much higher peak currents than possible during operations at FACET. For electron bunch lengths below $20\mu\text{m}$, the final bunch compression system in Sector 20 (Figure 1a) becomes a limiting factor for beam quality due to emittance growth through coherent synchrotron radiation (CSR). A simplified design for BC20E has been developed (b) which demonstrates greatly improved emittance preservation at high bunch compression in particle tracking simulations. To allow for the option of simultaneous delivery of electrons and positrons to the Sector 20 interaction region, a positron arm (BC20P) is also included: together they constitute the Sector 20 "flying saucer" chicane (Figure 4).

Figure 1: Existing BC20E electron compression chicane (left) and the redesigned BC20E with fewer magnets (right). Quadrupole magnets are shown in red, bends are blue, sextupoles are green. The yellow boxes in (a) show the accelerating structures at the end of Sector 19 and the transverse cavity in the chicane. For the re-designed optics, the transverse cavity is included in the beamline downstream of the chicane.

Electron System Design

The optics design for BC20E needs to meet multiple requirements:

- Pass a high peak current beam (>100 kA) or act as the final compression stage in generating a high peak current beam. The compression factor (R_{56}) should be tunable in the range $[0, +5]$ mm.
- Minimize transverse emittance growth due to CSR at high peak compression ($\Delta\epsilon < 5$ $\mu\text{m-rad}$).
- Correct for chromaticity and second-order dispersion due to the compression chicane and final focus magnets.

A “double dogleg” arrangement was chosen for BC20E as shown in Figure 2a for the $R_{56}=0$ configuration. This configuration uses fewer bending magnets compared with the previous design and avoids un-necessary over compression of the bunch in the center of the chicane. The simpler design has lower emittance degradation due to CSR when transporting a high peak-current electron beam. The trade-off is reduced R_{56} tuneability ($0: +5$ mm vs. $-10: +10$ mm), but this is still an acceptable range for all planned FACET-II experiments. Figure 2b shows the maximum $R_{56}=+5$ mm configuration, also showing the attached final focus system optics required for small beta optics at the experimental interaction region. This design has much lower betatron function amplitudes in the chicane ($\sim <100$ m). Lowering the maximum beta was found to be important during FACET operations to minimize beam loss and deliver stable and reproducible low-emittance beams to the interaction region. Two pairs of sextupole magnets (S1 and S2 sextupole re-used from existing design) are included for chromaticity and second-order dispersion compensation. A collimator is included immediately downstream of the first quadrupole magnet for bunch shaping and 2-bunch notch beam configurations as at FACET. A wiggler is included upstream of the final quadrupole in conjunction with a YAG screen for use as an energy spectrum monitor, again as used in FACET.

Figure 2: : Electron chicane optics with $R_{56}=0$ (left) and electron chicane and final focus optics, $R_{56}=+5\text{mm}$, $\beta^*=10\text{cm}$ (right).

Evaluation of BC20E Optics with Tracking Simulations

A start-to-end 6D particle tracking simulation exists for the TDR design of FACET-II. The Sector 20 optics were replaced with the new design here and the peak compression optimized using the phase of the L2 acceleration section. The longitudinal and transverse tracked phase space at the interaction point are shown in Figure 3. The tracking simulation includes treatment of wakefields, incoherent and coherent synchrotron radiation and longitudinal space-charge. With these new optics, a peak compression of 176 kA was achieved with a final transverse emittance of 7 μm -rad. This should be compared with a maximum peak current of 76 kA and transverse emittance of 13 μm -rad for the TDR Sector 20 design (each with an initial transverse emittance of 3 μm -rad from the injector).

Figure 3: Longitudinal (left) and transverse (right) phase space of 200k tracked macro-particles at the FACET-II interaction point.

Positron System Design (BC20P) and Flying Saucer Chicane Configuration

In a proposed future operation scheme, FACET-II is expected to deliver both electron and positron beams simultaneously to the Sector 20 interaction region. To achieve this, an electron bunch and positron bunch are co-accelerated through the

Linac spaced by $\frac{1}{2}$ of an s-band wavelength. An additional positron arm of the Sector 20 bunch compressor chicane (BC20P) has a path length difference of 5.24 cm to bring the two bunches into temporal alignment. The fine-spacing of the bunches is then controlled by differential control of the bunch energies. This design is like the previously proposed “sailboat chicane” design put forward for FACET, with some modifications. Due to the lower energy (10 GeV at FACET-II vs. 20.4 GeV for FACET) fewer magnets are required and the system is made 3.5 m more compact in z. The more compact design allows for a single transverse cavity (the XTCAV previously utilized in the FACET “W-chicane”) to be used downstream of the final chicane bend, common to both BC20E and BC20P. The new layout more resembles a “flying-saucer” topology than a sailboat, and has been renamed. See Figure 4.

Figure 4: : Plan view schematic of Sector 20 “flying saucer” chicane showing both BC20E and BC20P magnet placements. Red depicts quadrupole magnets, blue bends and green sextupoles.

3. Plasma Sources

3.1 What must the PWFA Collaboration do at FACET-II and an Overview of requirements for Plasma Sources based on experimental needs

Chan Joshi, UCLA

The Plasma WakeField Accelerator Collaboration [4] has embarked on a detailed study of the first experiments at FACET-II that are consistent with the DOE-Office of Science’s key milestones for beam-driven plasma accelerators as laid out in the Advanced Accelerator Development Strategy Report [5].

Introduction: Experiments on the Final Focus Test Beam (FFTB) and FACET have demonstrated that a beam-driven plasma wakefield accelerator operating in the nonlinear regime can accelerate electrons and positrons at high gradients and that a distinct bunch containing a significant charge can be accelerated with a relatively narrow energy spread with high efficiency.

The next challenge therefore is to show that the accelerated bunch from a single stage of PWFA can simultaneously achieve all the beam quality requirements for a future collider. This is the goal for the first major set of experiments at FACET-II proposed by the PWFA Collaboration.

Major physics goals:

- 1) Injection and extraction of the accelerated bunch without any significant increase in emittance. This requires matching the beam to the PWFA by using appropriately tailored plasma density ramps.
- 2) Minimum increase of the energy spread of the bunch and high drive-to-trailing bunch energy transfer efficiency. This requires optimization of beam loading of the wake.

Both these goals are critical elements of the research roadmap for Advanced Accelerator Concepts [5]. These experiments are entitled “Emittance Preservation of the Accelerating Beam in a High-Efficiency PWFA”.

Specific goals for the accelerating (trailing) bunch are:

- 1) Externally inject a matched low emittance bunch into the plasma wakefield accelerator.
- 2) Produce a gain of at least 10 GeV energy in less than one meter long plasma wakefield accelerator while minimizing the growth of the energy spread of the bunch.
- 3) Extract the accelerated bunch and transport it to the imaging spectrometer with minimum growth of its emittance.

Specific goals for the drive bunch are:

- 1) Determine if the drive bunch emittance and therefore the matched spot size needs to be increased to avoid undesirable injection of dark current into the PWFA cavity.
- 2) Propagate the drive bunch so that it transfers as much energy to the wake as possible, in other words propagate the drive bunch until it is pump depleted.
- 3) Determine the drive bunch to trailing bunch energy transfer efficiency.

Major theory/simulations goals are:

- 1) Develop the theoretical framework and the simulation tools to be able to achieve the physics goals.
- 2) Distribute these tools to the PWFA collaboration members.

Challenges:

Major challenges for the experimentalists are:

- 1) Design a plasma source with accurate density up- and down-ramps to achieve beam matching.
- 2) Design a technique for measuring small (0 (10%) changes to the accelerated beam emittance for a low emittance injected beam.
- 3) Perfect an online ability to accurately measure the separation between the drive and the trailing beam.
- 4) Design experimental techniques for in situ determination of the extent of the beam mismatch.

Major challenges for the FACET-II facility are:

- 1) Provide nominally 10 GeV drive and trailing bunches with the necessary charge, pulse width, bunch separation and emittance.
- 2) Provide focusing optics that can match the beam to the plasma density up-ramp.
- 3) Provide differential pumping that will eliminate the need to have thin metallic foils to separate the experiment from the high vacuum environment of the accelerator.
- 4) Provide adequate beam size and position monitoring diagnostics upstream and downstream of the plasma.

Why can this experimental campaign succeed at FACET-II?

The experimental goals are extremely difficult but the collaboration has the physics understanding [6,7,8], it has the simulations tools [9, 10] and it has demonstrated the critical physics of the experimental program in a series of previous experiments (albeit not simultaneously). The concept of beam matching was demonstrated in the very first PWFA acceleration experiment [11] where the beam's natural tendency to expand as it propagates (due to its emittance) was balanced by the transverse focusing force provided by the plasma ions. This happens when the beam's r.m.s. spot size $(\sigma_r)^2_{\text{matched}} = \epsilon_n (c/\omega_p) (2/\gamma)^{1/2}$. Here ϵ_n , ω_p and γ are the normalized beam emittance, the plasma frequency and Lorentz factor of the beam respectively.

Concepts of beam loading and high wake-to-accelerating bunch energy transfer efficiency were demonstrated [12, 13] in a landmark experiment on FACET. These experiments validated the predictions of the particle-in-cell (PIC) code simulations that are now being used to design the present experiments for FACET-II. The FACET-II facility will deliver the bunch parameters needed to simultaneously achieve all the goals stated above (see Table 2).

Table 2: Drive and Trailing bunch parameters for FACET-I and -II. The efficiency is defined as the wake to the trailing bunch energy transfer efficiency.

Parameter	FACET	FACET-II
<i>Drive Beam</i>		
Energy [GeV]	20	10
Charge [nC]	2	1.6
Normalized Emittance [μm]	$\sim 200 \times 50$	$\sim 7 \times 3$
Pump Depletion	No	Yes
<i>Trailing Beam</i>		
Bunch Charge [nC]	>0.5	0.5
Energy Spread [%]	~ 5	~ 1
Energy Gain [GeV]	9	>10
Efficiency [%]	30	50
Emittance Preservation	No	Yes

The key improvement is that FACET-II will deliver far smaller transverse emittance beams whose emittance growth can be quantified experimentally. For first stage of

the experiment, the beam loading was optimized by assuming a pre-formed plasma of density $4 \times 10^{16} \text{ cm}^{-3}$ and the spacing between the (suitably matched) drive and trailing bunches was adjusted until near perfect flattening of the accelerating field was obtained and, with it, the smallest increase in the energy spread. The result is shown in Figure 5.

	Drive Bunch	Trailing Bunch
Energy [GeV]	10	10
Peak Current [kA]	15	7.5
Normalized Emittance [μm]	50	50
Bunch Length [μm]	14	8
Transverse Size [μm]	3.6	3.6
Bunch to Bunch Separation [μm]	150	
Plasma Density [e^-/cm^3]	4×10^{16}

Figure 5: A pair of matched 10 GeV beams propagating through a plasma excite a fully blown-out nonlinear wake. The beam loading of the wake caused by the trailing bunch fattens the longitudinal field at the back of the wake and accelerates the electrons at the same rate, minimizing the energy spread. After ~ 40 cm of propagation the drive bunch is energy depleted whereas the trailing bunch has doubled its energy.

Once the acceleration process was optimized, the matching section was designed as follows. The density profile of the matching section (or density ramp) was approximated by an incomplete gamma function [Ref: Numerical Recipes] and the evolution of the Courant-Snyder (C-S) parameters α , β and γ of the bunches was followed through 100 μm thick sections of the density ramp. As the plasma density drops, the beam size slowly increases until the plasma density is too low. At that point, the beam rapidly increases in size as if it were propagating in vacuum according to $(\sigma_r)^2 = (\sigma_r)^2_{\text{min}} (1 + (s/\beta^*)^2)$ where β^* is the Rayleigh range of the focusing optic and σ_r, min is the smallest spot size at the vacuum waist of the bunch and s is the distance from the focusing optic to the plasma.

Figure 6: The evolution of the plasma density, beta function, alpha function and the spot size of the witness beam in the plasma ramp. Left: at the entrance; right: at the exit. The input beam energy at the entrance is 10 GeV.

Figure 6 shows the variation of the spot size and the C-S α and β parameters at the entrance (10 GeV beams) and the exit (trailing bunch now at 20 GeV) of the plasma. Here the incomplete gamma function of order 15 has been used.

This calculation gives a β^* of 3.9 cm, $(\sigma_r)_{\min} = 4.4 \mu\text{m}$ and a beam spot size of $260 \mu\text{m}$ at the final focusing quad that is $s = 7 \text{ m}$ from the plasma. These ramps are imported into QuickPIC and now the simulation rerun. The simulation conditions are shown in Figure 5.

	Drive Bunch	Trailing Bunch
Energy [GeV]	10	10
Peak Current [kA]	15	7.5
Bunch Charge [nC]	1.6	0.48
Normalized Emittance [μm]	10	10
Bunch Length [μm]	12.8	6.4
Transverse Size [μm]	21	21
Beta [m]	0.9	0.9
Bunch to Bunch Separation [μm]	150	
Plasma Density [e^-/cm^3]	4×10^{16} with ramps

Figure 7: The plasma and the beam parameters used in the QuickPIC simulation to demonstrate emittance preservation of a matched beam in a PWFA.

Figure 6 shows the spot size variation of the trailing bunch and its emittance change within the plasma up to the end of the exit density downramp. There is no discernable emittance growth.

Figure 8: Variation of the beam spot size and the normalized emittance in a 40 cm long uniform preformed plasma with density ramps. The Drive bunch transfers almost 90% of its energy to the wake while the trailing bunch extracts 50% giving an overall efficiency of 45%. The energy spread of the bunch is just 1%.

Experimental Concerns:

1) In the experiment an unmatched beam will undergo spot size oscillations and if there is energy spread on the beam this will lead to emittance growth. Figure 9 shows the effect of variation of the ramp density scale-length $L=(ne/(dne/dx))$.

The green curve shows the optimum profile with $L=13.2$ cm while the other curves show either a steeper or a more relaxed plasma profile. Any mismatch from the optimum causes the spot size of the beam to undergo betatron oscillations [14]. These oscillations will in turn cause an increase in the betatron yield and provide the experimenters a parameter to minimize. Similarly, errors in β^* or in s also increase the betatron yield.

Figure 9: Any departure from the exact matching condition (a) leads to spot size oscillation of the beam (b) and thus an increase in the betatron radiation.

2) The kind of plasma source needed is not yet determined nor whether the plasma density profiles with the required accuracy can be produced. This is currently under investigation.

3) With the highly successful Li oven source, there is the issue of ionization of He atoms causing injection of dark current into the plasma cavity. If the drive bunch causes the ionization of the He atoms in the density upramp region, the focusing force may be affected near the beam axis and this may cause emittance growth of the trailing bunch. This is an analogous issue to ion motion. This is also being currently investigated.

4) In the past, thin Be windows have separated the plasma region from the high vacuum accelerator region. These foils can cause the beam emittance to grow and will almost certainly have to be removed and replaced with differential pumping. This too is under investigation for both the Li oven source and the static hydrogen source.

Summary:

The PWFA Collaboration has embarked on a serious study addressing the issue of emittance preservation of the accelerating beam in a high-efficiency Plasma Wakefield Accelerator. The progress described at the 2016 FACET Science Workshop is reported here. The next collaboration meeting in January 2017 will address issues of transverse beam instability, effect of energy spread of the beam,

self-ionizing vs. pre-ionized plasmas and the smallest emittance and change in the emittance that can be measured.

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3.2 Heat pipe ovens & Plasma Sources for FACET-II

Ken Marsh, UCLA

The majority of FACET experiments have used plasma sources that have been developed at UCLA for the last two decades of PWFA research at SLAC. A heat pipe oven provides a uniform tube of lithium vapor that can be ionized directly by the beam fields or pre-ionized by an appropriate laser pulse. Lithium has a first electron that is easy to ionize and a second electron that is very tightly bound ensuring that in most realizable conditions each lithium atom provides one electron to the plasma. The lithium vapor is created by boiling metallic lithium within the oven at temperatures of around 1,000 °C. The vapor is confined to the oven through a collisional process with a room temperature helium buffer gas. The vapor density is controlled by changing the buffer gas pressure and the length of the column is controlled by adjusting the total heating power going into the oven. These sources are stable and scalable over a wide range of densities (10^{14} – 10^{17} e-/cm³) and lengths (20cm – 200cm).

The vapor is typically pre-ionized by the FACET laser system. Uniform plasma profiles are created by focusing a few hundred milli-joules of 800nm light through an axicon. The axicon can be adjusted to provide an extended line focus matching the length of the vapor column. In the case where a hollow channel plasma is desired (e.g. positron acceleration experiments) the axicon is replaced by an axilens that creates a hollow laser beam with a transverse profile of a higher order Bessel function (typically order five).

The plasma provides not only the accelerating fields, but is also the strongest focusing element in the system. The middle of the heat pipe oven provides a uniform longitudinal density and when the plasma wake is formed, the focusing provided by the ion column is constant along the distance of propagation and proportional to the plasma density. At the ends of the oven, in the region where the lithium and helium are colliding, the lithium density drops following a profile proportional to a half Gaussian with full width of about 10cm. This density taper provides a tapered focusing region that aids in matching the high-energy beams into and out of the plasma. For experiments at FACET-II, this profile needs to be tailored with a high degree of precision as described in section 3.1. Various options for the heat pipe oven temperature and buffer gas species are being investigated to meet the requirements for next generation experiments.

In addition to heat pipe ovens, various gas cells are being investigated. Gas cells have some advantages: very homogeneous gas density, low background gas per shot, and the ability to iris geometry to tailor the density ramps for matching. R & D activities to be pursued were identified as: delivering very small betas to the

entrance of the cell, shaping the ramp profile, studying effects of low background gas density outside the cell, maintaining low vacuum pressure at the IP, investigating whether pinholes can withstand hot plasma, and studying pre-ionization laser optics with large $f/\#$.

Gas jets were also discussed as methods to provide relatively short high-density plasmas. Advantages are: better ability to withstand hot plasma and full access for viewing from many directions. R & D activities discussed were: methods to reach 10^{20} e-/cm³ uniform density over 5mm distances, density profile, ramp shape, the large amount of gas to remove, methods to maintain low vacuum around the IP, and comparison of shaped nozzle to conical nozzle design (requires plasma density diagnostic and Phasics wavefront density profile measurements).

The concluding comments suggested that ultrashort, low emittance beams create new yet interesting challenges for plasma sources. This presentation introduced only a few ideas, but there are more available. There is much R&D needed with many commonalities between experimental groups. Collaboration is encouraged to maximize progress and benefits to the entire FACET-II user community.

3.3 Laser ionized gas

Mike Litos, U.C. Boulder

In Feb. 2016, the DOE's Office of Science convened the Advanced Accelerator Concepts Research Roadmap Workshop in direct response to a recommendation by the HEPAP Accelerator R&D Subpanel. Out of this workshop came the Advanced Accelerator Development Strategy Report [5], which identifies beam emittance preservation in the plasma wakefield accelerator (PWFA) as one of the major milestones required for the development of a multi-TeV lepton collider. To address this challenge, we propose a solution based on precision tailoring of the spatial density profile of the plasma source, coupled with the ability to dynamically optimize it on the fly.

The demands put on the plasma source used in the PWFA are numerous. First and foremost, the bulk of the plasma source must have a uniform density that can be set to the percent level. It must also be sufficiently long to provide the desired amount of energy gain to the witness bunch, and it must be significantly wider than the transverse size of the wake. For typical beam-driven PWFA parameters, nominal bulk densities range from 10^{16} e-/cm³ to 10^{17} e-/cm³, extending tens of centimeters to a few meters in length with a transverse radius of at least a few hundred microns. Such a volume of plasma can be difficult to create in the lab. When additional requirements are placed on the longitudinal density profile at the periphery of the plasma source (for example, to preserve beam emittance), the task becomes even more challenging.

There are three common methods by which PWFA plasma sources are generated: 1) electrical discharge, 2) beam-induced ionization, and 3) laser-induced ionization. Of these, only the laser-induced ionization technique offers a clear path toward the goal of emittance preservation. In addition, it is also the only technique that can simultaneously satisfy the criteria necessary to facilitate high-brightness beam

injection (e.g. presence of multi-gas species), high-brightness radiation production (e.g. ability to produce a “wakeless” narrow plasma column), and the production of hollow channel plasma sources – a potential necessity for accelerating positrons with PWFA. It is also the technique most accessible to essential diagnostics that can directly monitor the plasma source and beam-plasma interaction. Finally, it is the only technique that offers the possibility of rapid, fine adjustment to the plasma density profile, a major boon for on-the-fly tuning and optimization.

In this technique, a room-temperature gas is ionized by the passage of a high-power laser pulse that travels along an axis collinear with the electron beam, some few picoseconds ahead of the electron beam. The concentrated energy in the laser pulse allows it to readily ionize noble gas atoms when focused to a small transverse size. Through sophisticated manipulation of the laser’s phase front, it can be made to ionize an appropriately long and wide column of noble gas plasma for a PWFA. Essentially, this scheme pushes nearly all of the technical challenges onto the laser system, which allows one to take advantage of the high degree of precision, control, and flexibility available in advanced modern optical systems.

Emittance preservation

The primary source of emittance growth for a beam accelerated in a PWFA arises from the non-uniform betatron frequencies associated with any non-zero energy spread in the beam. A “matched” beam has a spot size that satisfies the relation $\sigma_r = \epsilon_n / (k\beta \gamma)$ while inside the plasma source, where σ_r is the beam spot size, ϵ_n is the normalized beam emittance, $k\beta = k_p / \sqrt{2}\gamma$ is the betatron wave number, k_p is the plasma wave number, and γ is the relativistic Lorentz factor of the beam. If the beam is matched for its mean energy, then it will be unmatched for off-energy particles, leading to envelope beating for those unmatched particles. This is represented in transverse phase space as a rotation of the phase space ellipse. Each energy slice of the beam then rotates in phase space at a different frequency. If all energy slices initially occupy the same transverse phase space, they will have spread out in phase after several betatron periods, filling in a new, larger volume than the initial volume. This new volume is called the saturation emittance, and it can be calculated from initial conditions given a few reasonable assumptions, such as linear focusing inside the blowout wake.

Any amount of energy spread in the beam will lead to chromatic emittance growth within the plasma, but matching the beam to the plasma (by its mean energy) can minimize this emittance growth. Thus a specific and well controlled focusing of the beam into the plasma is critical to preserving its emittance. Similarly, a highly divergent beam with non-zero energy spread traveling through vacuum will experience significant emittance growth. This can present a problem if there is not a controlled exit from the plasma source, as the matched divergence of the beam inside the plasma tends to be large, satisfying the condition $\sigma_r' = \epsilon_n k\beta / \gamma$. Thus, it is clear that the key to avoiding deleterious emittance growth is the controlled focusing of the beam into and out of the plasma source. One way to achieve this is to carefully tailor the plasma density ramps at the entrance and exit (upstream and downstream) locations of the plasma source.

A recent numerical study by X. Xu, et al. [8] compared the emittance control capabilities of several different plasma ramp density profiles, and identified methods of optimizing the parameters for a family of profile shapes. The best among those considered has the form:

$$f(z) = (1 - (z - L)/l)^{-2}$$

For a given L, which corresponds to the full length of the density ramp, one can solve to find the optimal value for parameter l:

$$l = k_{\beta}^{-1} \left(\left(\frac{(N+1)\pi}{\ln \beta_i k_{\beta}} \right) + \frac{1}{4} \right)^{1/2}$$

and

$$L = l(\beta_i k_{\beta} - 1)$$

where β_i is the initial betatron function of the beam, and N is any positive integer.

Optical setup for laser-ionized gas

A Ti:sapphire laser system is used to achieve a sufficiently high intensity at the focal region of the laser to ionize the target gas. Such a system can generate 800 nm wavelength pulses with a peak power as high as a petawatt, though 1 – 10 terawatts is sufficient for the purpose of generating the PWFA plasma source. The intensities necessary to fully ionize gases such as hydrogen, argon, and helium are in the range of approximately $2 - 4 \times 10^{14}$ W/cm². Partial ionization rates can be calculated using the ADK formula.

In order to specify the necessary phase front manipulation of the ionization laser pulse (i.e. focusing scheme), one must first decide what the plasma density profile should look like. The chief concerns in this regard have already been discussed above, and primarily entail the bulk plasma length, width, and the longitudinal density taper at the entrance (upstream end) and exit (downstream end) regions. The necessary laser intensity profile needed to ionize this particular plasma profile can then be calculated with the ADK formula, and finally, the appropriate phase manipulation of the initial laser pulse can be reverse engineered to generate the necessary focus.

It turns out that one can very closely approximate the numerically calculated ideal laser intensity profile at the plasma source entrance with a Gaussian function of the form:

$$I(z) = I_0 A e^{\left(-\frac{|z-L|}{C}\right)^B}$$

where $I_0 = 4 \times 10^9 (E_i/Z^2)$ is the barrier threshold intensity, E_i is the ionization potential energy, Z is the nuclear residue. Using a numerical minimization over the region $30\text{cm} < z < 50\text{cm} = L$ and assuming that the gas is hydrogen, the best fit parameters are $A = 1.18$, $B = 0.358$, and $C = 10.8$. Figure 10 shows the idealized longitudinal plasma density profile and corresponding laser intensity profile, as well as the intensity profile corresponding to these best fit parameters and the corresponding plasma density profile that it would generate. The plasma density profiles are shown to be in excellent agreement. The ability to use an analytical

expression like Eqn. 3 to describe the target laser intensity profile will aid in the design of the focusing optics, reducing the amount of brute-force numerical minimization required.

Figure 10: Ideal density (blue line) and corresponding laser intensity (orange line) profiles for emittance preservation at the entrance to the PWFA plasma source. Approximated intensity (red line) and corresponding density (green line) profiles from the analytical profile described in Eqn. 3 are also shown.

The basis for the optimized focusing is an optical diffractive element (ODE) called an axilens that generates a pseudo-Bessel beam, but concentrates all of the energy of the initial laser pulse into a specific longitudinal focal region. An appropriately designed axilens or other similar ODE can produce the desired noble gas plasma density profile for a PWFA. The addition of an adaptive optic like a deformable mirror can then allow for subtle and precise phase alteration to vary the laser focus and thereby manipulate the plasma density profile on a shot-by-shot timescale, an impossible feat for the other two common types of plasma source. Figure 11 from Ref. [15] shows a setup similar to the one just described that was recently used to achieve a pseudo-arbitrary longitudinal intensity profile demonstrating the proof of concept, albeit with a significantly lower laser power than that needed for the PWFA plasma source.

Figure 11: (a) Setup used in Ref. [2] to obtain arbitrary longitudinal intensity modulation on their laser beam. (b) Experimental phase mask pattern. (c) Transverse intensity profile. (Right) Experimental on-axis intensity (red) compared to target profile (blue), showing good agreement between the two.

Members of the FACET-E200 PWFA collaboration have begun pursuing research into the laser-ionized gas plasma source, and the University of Colorado Boulder group in particular is leading this work. The goal of this research is to demonstrate emittance preservation in a PWFA for the first time at FACET-II, as well as demonstrate the efficacy of this plasma source for related purposes, such as high brightness beam injection, high brightness betatron radiation generation, and hollow channel plasma wakefield acceleration of positrons and electrons. The group will build upon previous work done at FACET and strive to perfect the techniques needed for the laser-ionized gas plasma source in time for use with the high energy electron and positron beams available at FACET-II.

3.4 Hollow channel overview and prospects

Spencer Gessner, CERN

Hollow Channel Plasma Wakefield Acceleration (HC-PWFA), was proposed as a technique for accelerating particle beams over twenty years ago. The hollow plasma channel has appealing properties for particle acceleration. The longitudinal fields are radially uniform, and there are no transverse forces due to background ions or on-axis plasma electrons. This circumvents a major issue for positron PWFA in uniform plasmas, where positrons are defocused by the background ions or experience a non-linear focusing force due to plasma electrons that are sucked into the beam volume.

Although HC-PWFA attracted interest as a theoretical concept, it was difficult to realize experimentally because it is challenging to produce a hollow channel plasma. FACET was the first experimental facility that combined ultra-relativistic positron beams with a laser that was suitable for creating a hollow channel plasma. The first experiments carried out at FACET showed that it is indeed possible to generate large amplitude wakefields inside the channel while preserving the quality of the positron beam that drives the wake. In a subsequent experimental run, two-beam acceleration of a trailing positron beam was demonstrated in the hollow channel wakefield.

FACET-II offers a unique opportunity to further develop HC-PWFA as a technique for accelerating positron beams. Experiments on HC-PWFA at FACET-II can be divided into two categories. First, there are improved First Generation experiments. First Generation experiments are those that have the same components as the HC-PWFA experiments carried out at FACET. This includes a uniform gas or vapor source, a high-intensity laser with a high-order Bessel profile, and an ultra-relativistic, ultra-short positron beam. Improvements to First Generation experiments include high-resolution plasma density diagnostics to resolve the shape of the hollow channel on a shot-to-shot basis, use of a high first-ionization energy gas as a source which enables experiments with high-charge positron beams, and further investigations of the shape and magnitude of hollow channel wakefields.

The Second Generation experiments that can be carried out at FACET-II aim to address specific challenges associated with the hollow channel wakefield. These include the formation of a truly hollow plasma channel and the suppression of the

beam break-up instability (BBU). Ideas for creating truly hollow channel plasmas include ablation of an empty dielectric or acoustic modulation of a gas. Both of these ideas can be tested in smaller labs before being attempted at FACET-II. The BBU may be suppressed with external focusing magnets. This concept is currently being explored analytically and in simulation.

In summary, experiments at FACET-II will deepen our understanding of HC-PWFA as a technique for accelerating particle beams, and in particular, positron beams. Experiments at FACET-II will allow us to set tolerances on beam offsets and channel asymmetries. Second Generation experiments may lead to novel solutions to well known challenges associated with HC-PWFA. Lastly, FACET-II is the only facility in the world that will be capable of carrying out HC-PWFA experiments with positron beams. It is therefore critical to continue these studies at FACET-II.

3.5 Steady-state, free-flow plasma targets **Jens Osterhoff & Lucas Schaper, DESY**

Steady-state, free-flow plasma targets were introduced in the context of future experiments at the FLASHForward facility at DESY. Physically, the gas-targets have similar characteristics to the capillary discharge sources used in many laser wakefield accelerator experiments, but without the electrical discharge for ionization. The physics requirements delineated were similar to section 3.1 in that the resulting plasma needs to be stable, have reproducible plasma density profiles and have no emittance spoiling characteristics such as thick vacuum windows. In discussing the ionization of hydrogen by 100fs laser pulses, it was pointed out that the hydrogen fragmentation dynamics need to be considered. Specifically, how does atomic and molecular behavior differ? And what happens in the special case of ultrashort (<100fs) ionization beams?

The first gas-target prototype has been fabricated and will be tested (and optimized for DDR and tailored capture / release). Hydrogen fragmentation dynamics and the importance of timescales of ionizing beams need to be considered. Further, even more attention is needed when dealing with multi-species challenges (e.g. for ionization injection). Diagnostics remain a challenge but plasma spectroscopy offers insight into plasma parameters and Stark broadening offers an alternative approach to diagnose in regimes relevant at upcoming high energy accelerators. Plasma lensing is also being studied by the FLASHForward group. First results show focusing and beam steering at gradients of about 760 T/m. Upcoming experiments in early November will gain additional insight by characterizing the lenses using a ~GeV beam at the Mainz accelerator.

3.6 Active plasma lenses at 10GeV **Jeroen van Tilborg, LBNL**

Magnetic lenses play a critical role in accelerator applications, where both strength & tunability are important. A discharge current flowing through a capillary produces a linear magnetic field gradient for a uniform current distribution. Such an active plasma lens is an “old” concept for ion beams. Active plasma lenses are attractive

due to tunability, symmetry, and strength. A recent experimental demonstration on Laser-Plasma Accelerated electron beams in 2015 has renewed interest in this old idea. Measurements of the energy-dispersed beam size as a function of beam to discharge delay reveal oscillations within the plasma lens and map the focusing strength as a function of time. Scanning the beam transversely across the lens and measuring the subsequent deflection is useful to map out the focusing gradient.

Active plasma lenses were proposed as unique solutions for: 1. Ultra-relativistic e-beams and 2. Rapid capture for both compactness and mitigation of ϵ growth. Some possible limitations discussed include: emittance degradation from beam-driven wakefields for dense e-beams and emittance degradation from non-uniform current within the lens. The on axis current concentration within the lens takes on a donut mode when the electron beam is over-focused. The required stability of the current systems is of the order of 0.5% rms jitter with respect to e-beam timing.

Active plasma lenses have been shown to provide strong gradients. In certain conditions ($<20\text{pC}$, $>\text{GeV}$, $>100\mu\text{m}$ beam size) they may prove ideal for compact & GeV applications. Further studies are needed to understand limitations resulting from wakefields and non-uniform current. Areas for improvement identified were more uniformity from optimized timing, pressure, diameter, and beam size. The LBNL group is also participating with the DESY group in a Nov 2016 collaboration at the Mainz accelerator (mentioned in section 3.5).

3.7 TeV/m **Jamie Rosenzweig, UCLA**

The LCLS style photo-injector electron source at FACET-II represents a significant upgrade over what was available at FACET. The smaller longitudinal and transverse emittance allow for the possibility of improved bunch compression and focusing. In fact, the attosecond regime can be reached with low charge e-beams. The greatly enhanced beam brightness can afford many benefits such as single spike, compact FELs or enhanced wavelength range for a given energy. New regimes for beams are being explored as new configurations are developed for FEL operation; coherent optical radiation, ionization of materials, new diagnostics etc. These higher brightness beams, when implemented at FACET-II, will provide ideal capabilities for experiments from wakefield accelerators to understanding the behavior of matter in extreme fields. Examples of new frontiers are ultra-high field atomic physics with 100 V/Angstrom fields and extreme plasma wakefield acceleration with TeV/m gradients.

3.8 Plasma diagnostics **Mike Downer, U.T. Austin**

E224 has successfully imaged ion wakes driven by nonlinear electron wakes. Ion wakes depend sensitively on the electron wake history, and determine the state of the plasma for subsequent drive bunches. Measurements of these wakes will play a strong role in determining the maximum repetition rate that can be supported. This will directly affect beam power considerations for future colliders and ultimately

suggest the level of engineering required to renew the plasma between one bunch and the next.

Some observations such as the long timescale response of the ion wakes need to be studied with simulations to reveal the underlying physics. At FACET, the E224 runs were mostly parasitic during other experiments. In FACET-II, the collaboration proposes visualizing electron and positron driven plasma wakes directly, taking advantage of increased sensitivity via a) phase-contrast and Faraday rotation imaging and b) 3D imaging via multi-probe computerized tomography. High probe beam quality will be paramount in achieving quality scientific results from these diagnostics (e.g. temperature-controlled transport, pointing stabilization).

4. Witness Injector

4.1 Requirements: Ipk, emittance, alignment, beam size, charge Mark Hogan, SLAC

The roadmap for future colliders based on advanced accelerators contains key elements for experiments and motivates FACET-II. One specific demonstration goal is the staging of multiple plasma cells together to reach very high energies. Some forms of staging have been demonstrated, notably with inverse free electron lasers, with the STELLA experiment at BNL at ATF, and in a recent LBNL LWFA experiment with low energy beams and a few percent capture efficiency. None of these experiments has addressed the issues of staging multi-GeV beams together with order 100% capture efficiency.

For beam driven PWFA, the natural first steps in staging multiple plasma cells are 1) understanding the tools, techniques and tolerances for preparing the drive and witness bunches, 2) injecting the drive and witness beams into the plasma and 3) dumping the spent drive beam while extracting the accelerated witness beam with preserved emittance.

At FACET-II, adding a few hundred MeV witness injector has been considered as a way to study these important questions before proceeding to a full multi-stage demonstration. The main points to study would be as follows:

Upstream of a single stage, the experiments would:

- Inject a high-brightness witness bunch from an independent source
- Use tailored current profiles for maximum efficiency
- Investigate tolerances on timing and alignment between the two beams

Downstream of the single stage, the design must:

- Dump the spent drive beam
- Extract and preserve the emittance of the accelerated witness beam

The initial configuration studied would inject a 100MeV electron beam behind the 10 GeV drive beam at the interaction point. The witness beam could have a

maximum peak current of 3kA and be focused to a transverse spot size of 10 μm . After many vigorous discussions at the workshop, it was concluded that the design should provide higher peak current to ensure that the witness beam can properly load the plasma wakefield. This will be the work of further study.

4.2 Zig zag compressor and peak current optimization

Vladimir Litvinenko, Stonybrook

This proposal is to develop an emittance-preserving system with high compression ratio for a future FACET facility. High quality electron bunches from such a system could be used for external injection as a witness bunch. Table I lists some of possible accelerator choices for an external injector. The Zig-Zag type compressor proposal [16, 17, 18] would significantly mitigate the effect of coherent synchrotron radiation on the beam transverse emittance. Studies have shown that it is possible to achieve 30-fold and higher compression of high charge bunches while preserving normalized transverse emittance on the sub- μm level. The goal is to compress the witness bunch to about 10 μm (~ 30 fsec) with peak currents from 3 to 10 kA.

If necessary, the possibility of suppressing energy spread growth from CSR could also be explored.

Figure 12: Sketch of the possible external injector with Zig-Zag compressor.

Table 3: Possible sources of FACET witness bunch

Option	Dedicated injector	LCLS II
Beam Energy, [GeV]	0.3	4
Bunch Charge , [nC]	0.1/1	0.1
Normalized emittance, [μm]	<1-3	<1
Bunch Length, [fsec]	300-3,000	~ 200
Peak current, [A]	~ 300	~ 500

The proposal is to design and simulate such a compressor for FACET-II and, if necessary, test a prototype with electron bunches in the ATF at BNL.

4.3 4 GeV option

Joe Frisch, SLAC

LCLS-II will make more beam than the FEL instruments can handle for some time. At the FACET-II experimental area in sector 20, the LCLS-II transport line will be

overhead. This presentation asked, and attempted to answer the question: Does it make sense to consider scenarios where FACET-II parasitically (symbiotically?) steals pulses and couples them into the FACET-II beam line? A kicker and a duplicate of the chicane used to bring the LCLS-II beam from the LINAC beamline to the bypass line could bring the LCLS-II beam collinear with the FACET-II beam.

The LCLS-II control and data acquisition systems are already designed to allow pulse stealing for diagnostics lines and to keep dump line paths verified. Directing 30Hz pulses to FACET should have no effect on LCLS-II experiments. The new components needed include a 30Hz kicker and “dogleg” line to move the beam axis, FACET-LCLS-II combining optics, and beam synchronization systems.

The nominal LCLS-II beam parameters are: 4-8GeV, 100-300pC, 500-1500A peak current. The LCLS-II accelerator uses superconducting cavities and can only change fields very slowly – not bunch by bunch. Still, the LCLS-II beam could be a very good probe: very low geometric emittance, low energy spread, at a convenient energy for plasma diagnostics. A highly stable and well diagnosed probe beam is important for understanding plasma physics. It has been demonstrated that plasma accelerators can generate very high gradients, but it has not been shown that they can operate with enough stability to be useful. If both the pump and probe beams are unstable, it can be very difficult to map out the plasma effects. Developing a viable optics for using the LCLS-II beam as a witness bunch will take accelerator physics effort. It is also not clear how the construction cost would compare with a separate 300MeV injector. A study is also needed to determine how much flexibility there is in the LCLS-II beams delivered to FACET-II and if the beam parameters (such as the peak current) can satisfy the user requirements.

4.4 LWFA probe beam & witness injector option **Wei Lu, Tsinghua**

The feasibility of a LWFA probe at FACET-II was discussed. Using the currently available FACET laser (or with minor upgrade), this technique can be relatively simple to implement. The laser parameters assumed were 30fs pulse duration with 500mJ or 1J on the gas target, and with good pointing stability. Gas targets with an open boundary or with thin windows would be needed. The phase stability of the injected beam is determined by the synchronization between the laser and electron beam driver. This has been measured to be of the order of a few 100fs.

Looking ahead to FACET-II, in a time frame of about 3 years, it can be expected that stable high quality fs electron beams can be relatively easily obtained, potentially with parameters such as: 100-500MeV (using a 0.3-2J 30fs laser), fs pulse duration (from 0.1-10fs), 1-100pC of charge, high peak current: ~1-10kA, 0.5-2% energy spread, small emittance: ~0.1-1 mm-mrad, and stable beams (assuming a stable laser!). As the field of LWFA continues to progress, the possibility of obtaining suitable probe beams with the FACET laser system should continue to be evaluated.

5. Diagnostics

5.1 EOS optimization

Mike Litos, U.C. Boulder

The longitudinal diagnostics available at FACET were the transverse deflecting cavity (TCAV), a THz Michelson Interferometer and an Electro-Optic Sampling (EOS) system. The TCAV has single shot resolution of $\sim 10\mu\text{m}$, but it is destructive and subject to chromatic distortions. The THz interferometer is an averaged, multi-shot technique with a resolution of $\sim 5\mu\text{m}$. It is non-destructive and subject to distortions from beam parameter fluctuations. The EOS is a single shot measurement with a resolution of $\sim 10\mu\text{m}$. It is non-destructive and subject to distortions from laser fluctuations.

The EOS spatially encodes the time-dependent intensity of the electron bunch transverse electric field onto a low power laser beam. The field of the bunch can be approximated as a half-cycle THz pulse. The THz induces birefringence in the EO crystal. Part of the laser pulse intersecting the crystal receives a polarization rotation. The electron beam profile is then decoded from the polarization pattern imprinted on the laser – see Figure 13.

Figure 13: Spatially encoded EOS. Figure from A. L. Cavalieri et al., PhysRevLeZ.94.114801(2005).

At the end of the FACET run, the EOS system was a powerful online tool for recording the spacing between two bunches on a shot-to-shot basis – see example data in Figure 14.

Figure 14: Example data from FACET EOS system showing statistics from over 1,000 shots. The separation between two consecutive positron bunches was measured and histogrammed indicating a mean separation of 135 μm with a standard deviation of 20 microns.

Issues requiring improvement for increased EOS performance at FACET-II:

- Laser intensity profile
 - Spatial filter with apodizer
 - Spatial light intensity modifier
 - Challenge: tedious setup; space
- Laser pointing jitter
 - Laser transport stabilization ("B3" location)
 - Challenge: requires engineering; cost
- Laser polarization quality and control
 - Extremely high extinction ratio polarizer array
 - Remote control and monitoring before & after crystal
 - Challenge: tedious setup; space
- Laser energy
 - Increased EOS pulse energy autonomy from main ionization laser pulse
 - Challenge: solution not obvious; safety restrictions

Additional refinements are possible with:

- Remote control and monitoring of pulse length
 - Remote control of compressor gratings
 - Two-photon diode
 - FROG or similar diagnostic
- More/optimized crystal options
 - High signal/Low res. for coarse timing (ZnTe)
 - Compromise signal/res. crystal (150-200 μm GaP)
 - Low signal/high res. crystal (50-100 μm GaP)

- Increased magnification/camera resolution
- Remote signal attenuation control
 - Motorized multi-ND filter flipper
- Beam position monitor at crystal location (OTR, YAG, etc.)
- Smaller laser incident angle w.r.t crystal face

In summary, the EOS system implemented at FACET has appealing advantages: single shot, high resolution and non-destructive. With great effort, a working EOS system was demonstrated at FACET with capabilities such as: two-bunch separation measurement with $\sim 10 \mu\text{m}$ resolution, electron to laser beam timing with $\sim 10 \text{ fs}$ resolution and coarse single bunch length measurements with $\sim 30 \mu\text{m}$ resolution. Suggested high priority improvements for an optimized and robust signal at FACET-II center around the: laser intensity profile, laser pointing jitter, laser polarization quality & control, and laser pulse energy control. Numerous other possible improvements were discussed. The suggested goal for the FACET-II EOS system are: high-resolution ($< 10 \mu\text{m}$) longitudinal profile measurements of every single shot.

5.2 Hybrid linac-laser-plasma diagnostics and kicker

Bernhard Hidding, University of Strathclyde

The E210 experiments combined the primary FACET electron beam, a pre-ionization laser pulse (300-500mJ) and several low energy ($< 10 \text{ mJ}$) laser pulses used to either inject the Trojan Horse electrons into the plasma wake, measure the relative timing via the EOS system or image the plasma wakefield evolution. Controlling the release of the electrons into the plasma wake through Torch (optically triggered density downramp injection) or Trojan Horse (optically triggered release directly into the wake) required spatially aligning all of the laser pulses onto the FACET electron beam trajectory with about $10 \mu\text{m}$ precision. The pulses then needed to be synchronized for simultaneous arrival. Thermal drifts of the laser transport system and the FACET tunnel environment made it necessary to develop robust techniques to achieve the alignment and then to monitor and correct for drifts over time. Several techniques developed by the E210 collaboration were reviewed.

In addition to the EOS system described in Section 5.1, a time-of-arrival plasma glow technique was discovered during experimental setup. When either the primary ionization laser or the Trojan Horse (TH) injection laser is turned on with a time of arrival well before the electron beam, there is a faint glow from the plasma recombination light viewable by CCD cameras. When the FACET electron beam arrives it “heats” the pre-ionized plasma, resulting in a much stronger recombination light signal. The relative intensity of the recombination light signal was used for spatio-temporal alignment of the TH laser and electron beam. This was found to be an extremely robust method that in practice just involved scanning the laser timing and measuring the plasma glow intensity on the CCD. After sorting shots by electro-optical sampling time-of-arrival measurement, this technique was confirmed to produce a real femtosecond time of arrival (TOA) between the e-beam and laser that could also be used for spatial alignment.

Misalignment between the FACET electron beam and the primary ionization laser can lead to a kick due to the plasma density gradients at the ionization boundary. The beam position monitors (BPM's) downstream of the plasma are used to calculate the electron beam vector. By displaying the current beam vector compared to the initial vector after alignment, the alignment could be continually adjusted to maintain the optimum interaction conditions. Future possible improvements to these techniques were discussed and included all optical kickers and inverse Compton low emittance beam diagnostics. Preparations for FACET-II can begin now with the existing Ti:Sapphire laser without waiting for electron beam in 2019. These techniques need many laser pulses with different parameters. It was suggested to add additional laser system(s) as opposed to continually splitting the primary FACET ionization laser. The "access challenge" at FACET-II (twelve hours per two weeks) will dictate that robustness and simplicity for all systems is the most critical concern. Some systems may need double or triple redundancy. As with the EOS system, improved vibrational/thermal stability is desired. Developing plasma sources with optical access from various angles will greatly benefit these types of experiments.

5.3 TCAV & Energy Spectrometer **Brendan O'Shea, SLAC**

The transverse deflecting cavity (TCAV) was the primary diagnostic for setting up and characterizing various single and double bunch experimental configurations. The time resolution depends on many factors including the kick amplitude imparted by the cavity, the beam energy, the machine optics from the cavity to the profile monitor downstream and the emittance of the beam in the plane of deflection. FACET-II will deliver beams with nearly 100 times smaller emittance and half the total energy resulting in improved resolution for single bunch measurements and improved contrast for double bunch configurations.

The FACET energy spectrometer consists of two quadrupoles followed by a dipole. The dipole disperses the beam according to its energy on a variety of profile monitors located on an optical table prior to the beam dump. The quadrupoles are set to form an imaging condition from the desired location at the experimental area to the profile monitor of choice near the dump table. The imaging condition ensures an accurate measurement of the energy spectrum free of contributions from transverse kicks at the experiment. The imaging condition holds for one energy and can be scanned to measure a wide range of energies. The magnification of the beam size from the experimental area to the dump is typically of order one in the vertical (energy dispersed plane) and seven in the non-dispersed (horizontal) plane. In practice, with careful calibration of the energy axis, additional information can be determined from the spectrometer images.

Under nominal conditions, the spectrometer images a waist to a waist. If the beam at the object plane at the interaction point is not at a waist, then the waist at the spectrometer will appear at an energy higher or lower than the set-point energy, e.g. if the beam waist is downstream of the object plane, the waist will appear at a

higher energy than the setpoint and if the waist is upstream of the object plane the waist will appear at a lower energy. This technique was often valuable in determining the location of the end of the plasma interactions where the beam transitioned from the ion column focusing to a free space drift.

Under nominal conditions, the horizontal beam size is minimum at the setpoint energy. Away from the design energy, the beam size increases proportional to the chromatic aberrations of the spectrometer and the beam divergence which is related to the beam emittance. The beam size increase vs energy can be used to measure the beam emittance averaged over a range of energies. The lower emittance FACET-II beams will have correspondingly lower emittance and thus require greater care with the CCD imaging system at the dump table profile monitors that measure the beam profile, as shown in Figure 15.

Figure 15: Simulated energy spectrometer images for an r.m.s. energy spread of 5%, 0.25m beta at the IP and 50μm normalized emittance for FACET(left) and 3μm normalized emittance at FACET-II (right).

5.4 FACET Diagnostic Experience

Nate Lipkowitz, SLAC

FACET Linac diagnostics were largely carried over from the SLC including Beam Position Monitors (BPM's), toroidal current monitors, phosphor profile monitors with analog TV cameras, and wire scanners. Diagnostics in the FACET beamline in S20 and around the experimental area were developed in conjunction with the experimental programs: Transverse deflecting cavity (TCAV), non-invasive energy spectrometer (SYAG), compact wire scanners, pyro-electric bunch length monitors and multi-function profile monitors using thin (1μm titanium OTR foils, 500 μm thick Ti OTR foils and 20μm thick Ce:YAG crystals).

The FACET control system was a hybrid architecture marrying the SLC control system (SCP) and EPICS controls for newer devices. Tools exist to pull data from legacy system diagnostics, correlate with EPICS measurements, scan magnets etc. It was noted however that there is little support remaining for the legacy SLC systems. The hybrid system works with some data rate limitations.

FACET operational experience and performance of the various diagnostic devices listed above was reviewed. FACET-II will pose new diagnostic challenges. The high-brightness electron beam from the RF photocathode gun will pose similar challenges to those at LCLS such as coherent OTR emission from screens due to

micro-bunching. No clear solution to this is known yet and FACET-II will likely have to use wire scanners at certain locations.

FACET-II will support two-bunch operation in two distinct regimes:

- e^- / e^- (60 ns) – bunch spacing comparable to SLC and similar to current LCLS two-bunch operation.
- e^- / e^+ (100 ps) – much harder, high bandwidth processing needed for many signals.

Extremely high peak currents may be generated, approaching ~ 100 kA, and the focused beam is imagined to damage beam-intercepting devices (screens, wires, windows). It is not yet clear how to measure this type of beam. Non-intercepting methods e.g. edge radiation interferometry are a possibility but need further study.

Many lessons were learned during FACET operation that should serve as a foundation for operations at FACET-II. Managing and controlling the configuration across maintenance days and experiment installation is important for meaningful results. Modern, supported diagnostics controls go a long way towards solving many of the limitations and headaches involved with data collection and analysis.

- Stability across shifts remains a problem at FACET and probably FACET-II:
 - Many drift sources are hard to identify (RF, alignment, BPM...)
 - Feedback is only as good as the measurement, and can mask or worsen problems
 - Source beam stability is paramount for experiments and for machine studies
 - Archive everything - finding correlations is an art and could be improved with some software development effort.
- Diagnostics generate lots of information:
 - Data storage and access are often a limitation - plan for more than you expect
 - Users and operations have different use cases and data flow needs, both should be considered

5.5 E200/E225 quad scan experience

Sebastien Corde, Ecole Polytechnique

The beam emittance can be measured with a multishot quad scan in the FACET spectrometer, if the transport matrix is properly adjusted.

Pros of this technique:

- Precise measurement, no assumption on energy dependence of beam parameters.
- Can resolve very low divergence beams because the transport matrix can be scanned over a very wide range (typically M12 from -20 m to +20 m). Same beam size resolution as the “butterfly” method, limited by the scintillator resolution and M11.

- Can be used to validate “butterfly” method, which is a single shot measurement.

Cons:

- It is a multishot measurement. Cannot detect rare shots with extremely small emittance. Needs relatively stable outgoing beams.
- Works for the x dimension, not for the y dimension. Shouldn't be a problem with more symmetric input beams.

Examples of this technique implemented at FACET are shown below in Figure 16.

Figure 16: Example quad scan measurements illustrating the range of parameters that can be measured as illustrated by a positron beam after the plasma (left) and an electron beam with no plasma (right).

Possible improvements suggested for FACET-II include:

- Remove windows downstream of the plasma (Be window).
- Increase M11 as much as possible, to increase beam size resolution in the object plane.
- Improve beam size resolution in the image plane.
- Add more quadrupoles in the dumperline. This would allow an optimization to reduce chromaticity in the y dimension over a wider energy bandwidth.

Quad scans are usually necessary to properly characterize the decelerated energy spectrum and energy transferred to the plasma by the drive beam. Emittance measurement is possible with a quad scan in a dispersed region. This was demonstrated at FACET. This can be very promising for FACET-II emittance preservation studies with normalized emittance down to a few micrometers. This technique is an excellent complement to “butterfly” measurements. Several improvements are possible for FACET-II: remove Be window, increase M11 and improve the scintillator/profile monitor resolution.

5.6-5.7 E-210 Experience with butterfly technique

Carl Lindstrom, Oslo and

E-217 experience with butterfly technique

Navid Vafaie, Stonybrook

FACET hosted multiple experiments on electron beam injection, including E210 (Trojan Horse-injection experiment) and E217 (Ionization injection experiment). Their emittance was expected to be very low: $O(1 \text{ mm-mrad})$ or lower. Measuring such low emittances is very challenging, especially at low energies. However, the two groups independently came up with a method for extracting the available emittance information.

Both approaches used variants of the so called butterfly technique to analyze their images. The E210 method was based on modeling the beamline downstream of the plasma including the effects of windows. The first step is to do Gaussian fits to find the beam width (σ_x) at each energy. The second step is to find the best fit parameters (β , ϵ_N , s^*) by comparing the modelled beam widths to the measured beam widths.

Figure 17: (Top) Example fits to a High emittance, high energy shot (normal butterfly method) and (Bottom) Low emittance, high energy shot (needs the new method)

These techniques run into limitations at low energies but there are opportunities to gain information and get estimates. The method works best around and above the emittance resolution determined by scattering through the beamline windows. However, below the emittance resolution, it is also possible to gain information. By making assumptions about the divergence before the window (upper/lower bounds) it is possible to estimate the emittance before the window (upper/lower bounds). This method is used for the E210 Trojan Horse injection experiment.

E217 also used an optimization routine to estimate the parameters of the beam consistent with the beam size observed in a high resolution spectrometer. The emittance of the injected beam from E217 was estimated to be $5 \mu\text{m}$, much smaller than the incoming drive beam ($>100 \mu\text{m}$). Looking ahead to FACET-II, it is expected that the imaging spectrometer can be used to measure the emittance growth of the witness beam in the two bunch experiment in FACET-II to an accuracy of tens of percent. The more mismatched the beam is, the harder it is to measure the emittance growth.

Summary and recommendation for FACET-II: eliminate the windows that isolate the experimental area from the other vacuum systems. Measuring emittances for low emittance, low energy beams is challenging. One main goal for FACET-II is to demonstrate low emittance PWFA beams. This will require reliable low-emittance measurement techniques. Accordingly, FACET-II should avoid beam windows downstream of the plasma, at least when studying low emittance beams.

5.8 Prospects for crystal channels

Brendan O'Shea, SLAC

Crystal channeling can be used to guide low divergence beams using the potential formed between the lattice planes of specific crystals. Each crystal is cut so that the atoms line up along the beam direction. When the electrons are close enough to the atoms, the potential is attractive. Electrons with sufficiently small transverse velocity are trapped in the potential. When the crystal is bent at small angles, the guided electrons will follow the bend of the crystal. In principal, this technique could then be used to place bounds on the beam emittance. For a given beam size at the entrance of the crystal, only beams with a low enough divergence (corresponding to a low enough emittance) will be guided. Looking at a profile monitor well downstream of the crystal, the number of electrons guided and deflected by the bent crystal can be used to estimate (or at least place upper limits on the beam emittance). If two populations of electrons impinge upon the crystal, e.g. a drive beam with large emittance and a low emittance injected beam, only the low emittance injected electrons will be guided.

In the analysis presented, the potential was modeled as a Gaussian shape and various issues that can lead to de-channeling were discussed. To have confidence that this technique can offer a viable way to separate an injected beam from the spent drive beam in a PWFA, more work needs to be done to understand the following:

- Shape of the potential
- Beam transfer from plasma to vacuum and distance from plasma to crystal
- Effect of beam on crystal
- String re-ordering due to temperature
- String damage
- A better understanding of electron-string collisions

6. Low Emittance Diagnostics

6.1 E200 betatron radiation experience

Sebastien Corde, Ecole Polytechnique

The principle of betatron radiation in beam-driven plasma accelerators was reviewed. The constant focusing force in the ion cavity (1-100 MT/m) causes electrons to oscillate around the propagation axis. Due to their oscillatory motion, electrons emit synchrotron-like radiation, called betatron radiation. Typical

radiation properties are: mrad divergence, large K wiggler regime, broad band synchrotron spectrum, critical energy of ~ 10 MeV and 10^{10} - 10^{11} photons.

For typical experimental parameters at FACET, betatron radiation was strongly peaked in the gamma-ray region. The experimental setup for gamma-ray measurements included apparatus to measure the spatial distribution and the critical energy – see Figure 18. Information gained from betatron radiation measurements included evidence for electron beam self-focusing and beam symmetrization.

Figure 18: FACET diagnostics were able to resolve the spatial intensity of the betatron spectrum (left), coarse spectral measurements with various filters (center) and fit the spectrum to models to infer information about the average betatron motion of the beam (right).

The experience with betatron gamma-ray measurements at FACET demonstrated that information can be obtained on self-focusing, beam symetrization, matching, and emittance. To study low emittance beams at FACET-II, detectors for keV and MeV photons are needed along with a stack calorimeter to characterize the entire shower produced by the betatron gamma-ray beam. Low emittance beams will be in the low K undulator regime and the angularly-resolved spectrum can be very important as well.

6.2 Gamma spectrometer Felicie Albert, LLNL

The principle of gamma-ray sources based on Compton scattering were described and the performance of T-Rex, LLNL's first Compton gamma-ray source was reviewed. Estimations indicate 105 photons/shot (based on calibrations with ^{137}Cs source @ 662 keV). One potential application of such a photon source is Nuclear Resonance Fluorescence (NRF) that can provide isotope-specific contrast. Gamma-rays in the 0.5-3 MeV range are especially attractive since they are both highly penetrating and non-activating.

Betatron x-ray characterization involved measuring the electron spectrum with a two-screen spectrometer and measuring the spectral and spatial information on the betatron beam with a stacked image plates spectrometer. Spectral analysis provides information about betatron oscillation amplitudes without any spatial information, but the beam profile is used to retrieve the spatial orientation of the oscillations.

The combined spectral and spatial analysis provides a tomographic reconstruction of electron trajectories.

Development of a betatron radiation source at LCLS has recently progressed to operations. Examples of the physical mechanisms studied with betatron radiation at LCLS include SiO₂ heated by an optical laser and Fe heated by an X-ray FEL.

6.3 Betatron radiation in wakeless regime

Jamie Rosenzweig, UCLA

The goal is to create and study coherent betatron oscillations through their radiation in various undulator configurations. There is the potential to create a new class of very high field undulator ($K \gg 1$), enhance short period low- K micro-undulators to $K \sim 1$ regime (MEMS undulators at UCLA) or create a helical undulator. This represents a chance to explore fundamental beam-plasma physics through superposition of PWFA and undulator interactions. The so-called ‘Wakeless plasma’ is the key innovation. In a wakeless plasma, the blow-out radius is much larger than the diameter of the plasma column. In this regime, the plasma electrons that are blown out by the drive beam do not come back to the axis. The lack of radial current means there is no longitudinal component of the electric field and motion is dominated by the ion column and not the energy changes due to the wakefield.

A betatron radiation double differential spectrum (DDS) measurement setup was proposed for FACET-II, based on the ICS demonstration by a UCLA-ATF experiment. A bent crystal disperses the betatron radiation and angular information is obtained along the slit (inside calorimeter stack for FACET-II case). It has been shown that a large wavelength and angular spectra range can be resolved – see Figure 19. It was also proposed that the beam emittance can be recovered. The central betatron wavelength is proportional to the beam energy, and the linewidth of the radiation is proportional to the beam emittance. Assuming Gaussian betatron amplitude distributions, the rms line-width gives emittance through spread in K redshifts. Numerous possibilities for injection to produce the off-axis beam that will seed the radiation process were discussed and many have already been attempted at FACET. These activities are considered to be synergistic with other uses of betatron radiation. They are highly leveraged off of previous UCLA and collaborator experience, including E210 and other FACET experiments.

Figure 19: Example of spatial and spectrally resolved betatron radiation for an experiment at the BNL ATF.

6.4 B.N.S. Considerations for loaded PWFA **Sergei Nagaitsev, FNAL**

The title of this talk was “BBU in a blow-out regime: a proposal for an experiment”. The talk was based on an earlier paper [19]. While the theory of the beam breakup instability is well developed (see, e.g. Reference [20]), it requires knowledge of the transverse wakefields inside the accelerating bubble. Unfortunately, the established classical theory of wakefields in an accelerator environment does not properly address the complicated problem of wakefields inside a nonlinear plasma bubble.

An attempt was made to overcome this difficulty by using a combination of the expression for the short-range wakefield derived for a dielectric channel, and an analytical model for the electromagnetic field in the blowout regime of PWFA published by Lu et al [21]. This approach needs to be corroborated with 3D computer simulations of PWFA. Using the analytical wakefield and the growth rate for the instability, an estimate was made for the parameters of the E200 proposed experiment at FACET-II (see Section 3.1). The conclusion was that at the acceleration distance of 60 cm, the initial betatron oscillation amplitude of the witness bunch would be amplified by 10 times. These analytical predictions can be tested in future experiments at the FACET-II facility.

The second part of his talk discussed an option of intentionally introducing an energy spread in the beam (the so called BNS damping). While this may be helpful for mitigating the instability, according to the theory, it would result in relatively small energy transfer from the driver to the witness field.

In subsequent discussion at the workshop, it became clear that there is a mismatch between the established analytic approach in the classical theory of wakefields and instabilities in traditional accelerators, and the methods and language utilized in the PWFA community by those who run the simulations. It would be beneficial for both communities to establish a better collaboration, and to commonly address the BBU problem.

7. Computation

7.1 Needs and challenges for modeling FACET-II and Beyond **Warren Mori, UCLA**

There were three talks that addressed the computational challenges and needs for possible experiments on plasma-based acceleration at FACET-II. The first talk addressed the near term and longer term computational needs for a vibrant program on plasma wakefield acceleration (PWFA). There was an overview of the computational methods, the physics that needs to be included into the simulation techniques, and how to estimate the computational resources required for PWFA simulations. The near term needs are for designing and interpreting experiments on FACET-II, while the longer term needs are for designing a PWFA based linear collider (PWFA-LC) which will require beam and plasma parameters beyond the

reach of near term experiments. The overall conclusion is that the near term needs for modeling FACET-II do not require exascale class computing and can be met through existing software.

A useful table was presented to illustrate the computational needs for simulating generic PWFA experiments for FACET-II and PWFA-LC stages using a fully explicit 3D PIC codes such as OSIRIS and a quasi-static PIC code such as QuickPIC. The assumption is that the simulations require domains $25 c/\omega_p \times 20 c/\omega_p \times 20 c/\omega_p$ in size, the cell sizes need to $\sim .025 c/\omega_p$ in each direction, and that the plasma length needs to roughly match the pump depletion length. In units of c/ω_p , the pump depletion length scales as the λ of the drive beam which is 20,000 (10 GeV) for FACET-II and 50,000 (25 GeV) for a staged PWFA-LC. It is also assumed that there are 8 particles per cell. For the OSIRIS cases the time step is chosen to be at the Courant limit while for QuickPIC the time step is chosen to resolve the betatron oscillations of the drive beam. These assumptions then lead to the estimates for the number of particle pushes shown in Table 4. To estimate the number of core hours it is assumed that each particle push will take ~ 300 ns (which is the speed of OSIRIS for so called second order particle shapes) and $\sim 1,000$ ns for QuickPIC. These are lower bounds as load balancing issues are assumed to be negligible. These estimates show that each QuickPIC simulation of a FACET-II experiment requires only several thousand core hours. An OSIRIS simulation requires less than 106 core hours. These requirements are similar for either electron or positron drive beam experiments.

Table 4: Computational requirements to simulate a FACET-II stage and a PWFA linear collider (PWFA-LC) stage using QuickPIC and OSIRIS.

3D simulations	OSIRIS:pushes	QuickPIC:pushes	OSIRIS: core hours	QuickPIC: core hours
FACET-II	7×10^{15}	1×10^{13}	5.9×10^5	2.8×10^3
PWFA-LC	1×10^{21}	5.6×10^{16}	8.7×10^{10}	1.5×10^7

On the other hand, the computational demands for a linear collider simulation can be much more challenging. As described in this talk, a beam loading scenario that provides excellent energy transfer efficiency from the drive beam to the trailing beam while possibly maintaining excellent beam quality loads a trailing beam into the ion column of a nonlinear wakefield. For linear collider parameters, the matched spot size of such a beam under the influence of the focusing forces of the ion column is ~ 100 nm. In order to resolve this the cell sizes must be $\sim .0005 c/\omega_p$. Based on this, the computational needs for modeling a single stage of a PWFA-LC pushes the limits of leadership class computing facilities for quasi-static methods and is outside the existing resources for fully explicit methods. For this problem, mesh refinement may be useful. For other beam loading scenarios for which the trailing beam is not narrow, the computational needs are similar to those of FACET-II experiments.

In both the talks of Jean-Luc Vay (Section 7.2) and Weiming An (Section 7.3), methods for improving the software capabilities were discussed. For OSIRIS, QuickPIC, and WARPX there are existing efforts such that these codes can take

advantage of emerging (both near term and longer term) many core technologies including GPUs and Intel Phi. WARPX is attempting to implement adaptive mesh together with boosted frame to make full 3D simulations possible. There were discussions at the workshop regarding how differences in PWFA and LWFA modeling may affect the speedups possible from the boosted frame technique for PWFA simulations. Determining whether these speedups are larger than those offered by the quasi-static approach is not clear. Additionally, Weiming An discussed how adaptive mesh refinement, adaptive particle loading, and adaptive time steps, could significantly improve the capabilities of QuickPIC. In his talk Weiming An also mentioned that QuickPIC will be open source in the very near future.

In summary, the near term needs for FACET-II modeling can be met with QuickPIC and full 3D and quasi-3D OSIRIS simulations. These codes have been widely used within the previous FACET program. The needs of PWFA-LC simulations can be met with enhancements to QuickPIC. If the development of WARPX is successful, then it may also play a role in PWFA-LC simulations.

7.2 Benefits of the Exascale ECP and CAMPA programs to the modeling of PWFA

Jean-Luc Vay, LBNL

The second talk described an ambitious effort to develop a code called WARPX that incorporates adaptive mesh and boosted frame techniques as well as the use of low level libraries that include a hierarchy of parallelization that can take advantage of many core technologies.

7.3 Current status and near term needs for modeling FACET-II

Weiming An, UCLA

The last talk provided details and the computational resource needs for simulating the planned two bunch experiments and down ramp injection experiments described earlier in the Workshop. These were simulated with QuickPIC and/or with OSIRIS. A discussion of the current status and possible near term enhancements of these codes was also given.

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