Ultra-Intense Beams at FACET-II and Experiments to Probe High Field Quantum Electrodynamics far beyond Schwinger Fields

Vitaly Yakimenko
September 5, 2017

ExHILP 2017
A Roadmap for Future Colliders Based on Advanced Accelerators
Contains Key Elements for Experiments and Motivates FACET-II

Key Elements for PWFA over next decade:

- Beam quality – build on 9 GeV high-efficiency FACET results with focus on emittance
- Positrons – use FACET-II positron beam identify optimum regime for positron PWFA
- Injection – ultra-high brightness sources, staging studies with external injectors
- Develop PWFA demonstration facility
FACET-II: Premier R&D facility for PWFA

FACET Highlights (2012-2016 experimental program):
High impact results on efficient acceleration of e- and e+ in plasma:
✓ Mono-energetic e- acceleration
✓ High efficiency e- acceleration (Nature 515, Nov. 2014)
✓ First high-gradient e+ PWFA (Nature 524, Aug. 2015)
• Demonstrate required emittance, energy spread (in preparation for Nature)

FACET-II Timeline:
✓ Nov. 2013, FACET-II proposal, Comparative review
✓ CD-0 Aug., 2015
✓ CD-1 Review Oct., 2015
• CD-4 2022

Four researchers became professors:

FACET-II will operate as a National User Facility with experimental program between 2019 and 2026
PWFA Research Priorities at FACET-II

**Emittance Preservation with Efficient Acceleration**

**FY19-21**
- High-gradient high-efficiency (instantaneous) acceleration has been demonstrated @ FACET
- Full pump depletion and preservation of emittance at µm level is planned as the first high impact experiment

**High Brightness Beam Generation & Characterization**

**FY20-22**
- 10’s nm emittance preservation is necessary for collider applications
- Ultra-high brightness plasma injectors may lead to first applications of PWFA technology

**Positron Acceleration**

**FY21-24**
- Only positron capability in the world for PWFA research will be enabled by Phase II
- Develop techniques for positron acceleration in PWFA stages

**Staging Studies**

**FY22-25**
- Independent witness injector planned to be added to FACET-II as an AIP project
- Enables studies of staging challenges (timing, alignment,…) and high transformer ratio

FACET-II Layout and Beams

### Beam Parameter

<table>
<thead>
<tr>
<th>Beam Parameter</th>
<th>Baseline Design</th>
<th>Operational Ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final Energy</td>
<td>10 GeV</td>
<td>4.0-13.5 GeV</td>
</tr>
<tr>
<td>Charge per pulse</td>
<td>2 nC</td>
<td>0.7-5 nC</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>30 Hz</td>
<td>1-30 Hz</td>
</tr>
<tr>
<td>Norm. Emittance $\gamma\varepsilon_{x,y}$ at S19</td>
<td>4.4, 3.2 $\mu$m-rad</td>
<td>3-6 $\mu$m-rad</td>
</tr>
<tr>
<td>Spot Size at IP $\sigma_{x,y}$</td>
<td>18, 12 $\mu$m</td>
<td>5-20 $\mu$m</td>
</tr>
<tr>
<td>Min. Bunch Length $\sigma_z$ (rms)</td>
<td>1.8 $\mu$m</td>
<td>0.7-20 $\mu$m</td>
</tr>
<tr>
<td>Max. Peak current $I_{pk}$</td>
<td>72 kA</td>
<td>10-200 kA</td>
</tr>
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</table>
FACET-II Beam will Access New Regimes

Low-emittance (state of the art photoinjector) and ultra-short (improved compression) beam will generate:

- >175 kA peak current (~1 µm long)
- ~100 nm focus by plasma ion column
- $\sim 10^{12}$ V/cm radial electric field ($E_s=1.3\times10^{16}$ V/cm)
- $\sim 10^{23}$ cm$^{-3}$ beam density
- $\sim 10^{25}$ W/cm$^2$ peak intensity
### Four Options to Study High Field QED at SLAC

**Option 1: FACET-II beam and existing laser**  
**FY19-21**
- 20TW synchronized with beam laser is available in FACET-II experimental area
- Can start with start of FACET-II - all hardware exist

\[ \chi \approx 0.3 \quad (\chi = \frac{E_p}{E_s}) \]

**Option 2: Upgraded Laser and 10GeV beam**  
**FY19-21**
- Experimental Laser at FACET-II can be upgraded to 100-300TW
- Alternative location with LCLS beam

\[ \chi \approx 1-3 \]

**Option 3: 10GeV FACET-II beam and 300MeV “witness injector”**  
**FY22-25**
- 175kA FACET-II beam focused to 100nm
- e-beam probe in e-beam field

\[ \chi \approx 0.1 \]

**Option 4: 100GeV collider e-e+ with \( \chi \approx 103 \) !**  
**Future facility \( \approx 20 \) year**
- Full breakdown of perturbation theory
- So far theoretical calculations are impossible

\[ \chi > 10^3, \; \alpha \chi^{2/3} > 1 \]

*V.I. Ritus, ZhETF, Vol. 57, No. 6, p. 2176, 1970*
**Option 4:**

### 100GeV collider e⁻e⁺ (Future facility ~10-20 years)

**Beam field:**
- \( \gamma = 2 \times 10^5 \), \( I_b = 10^6 A \), \( \sigma_r = 10 \text{nm} \), \( \sigma_z = 100 \text{nm} \)

\[ E_r = \frac{I_b/c}{2\pi \varepsilon_0 \sigma_r} \approx 6 \cdot 10^{13} V/cm \]

\[ \chi = 2\gamma \frac{E_r}{E_s} \approx 1800 \]

\[ g = \alpha \chi^{2/3} \approx 1 \]

\[ D = \frac{2r_e N_e \sigma_z}{\gamma \sigma_r^2} \approx 15 \]

\[ \Upsilon = \frac{5}{6 \alpha (\sigma_x + \sigma_y) \sigma_z} \approx 10^3 \]

\[ \delta = \frac{6 \alpha \sigma_z}{5\sqrt{\pi} \gamma \lambda_c} \approx 3 \]

**Average energy loss in quantum regime (\( \Upsilon > 100 \))**

\[ n_b = \frac{N_e}{(2\pi)^{2/3} \sigma_r^2 \sigma_z \gamma} \approx 10^{31} \text{cm}^{-3} \]

\[ \frac{2}{\lambda_c^3} \approx 3 \cdot 10^{31} \text{cm}^{-3} \]

**Perturbation theory does not work**

**HEP in the presence of extreme field is unexplored**

**Beam disruption parameter**

**Beamstrahlung parameter**

V.I. Ritus, ZhETF, Vol. 57, No. 6, p. 2176, 1970


V. Yakimenko, ExHILP, September 5, 2017
**FACET-II Science Workshop 2017**

**17-20 October 2017**

[Email: hogan@slac.stanford.edu](mailto:hogan@slac.stanford.edu)


**Agenda**

<table>
<thead>
<tr>
<th>Tuesday</th>
<th>Wednesday</th>
<th>Thursday</th>
</tr>
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<tbody>
<tr>
<td><strong>Start Time</strong></td>
<td><strong>Session Topic</strong></td>
<td><strong>Presentation</strong></td>
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<tr>
<td>09:00 am</td>
<td>Simulation Codes</td>
<td>QUICKPIC</td>
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<tr>
<td>09:30 am</td>
<td>Simulation Codes</td>
<td>OSIRIS</td>
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<tr>
<td>10:00 am</td>
<td>Simulation Codes</td>
<td>WarpX &amp; Exascale</td>
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<tr>
<td>11:00 am</td>
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<td>VSIM</td>
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<tr>
<td>11:30 am</td>
<td>Simulation Codes</td>
<td>8 Years of Beam-Driven Wakefield Simulation - lessons learned, reduced models, and future plans</td>
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<td>12:00 pm</td>
<td>New Directions @ FACET-II</td>
<td>Active plasma lenses - limitations on beam energy/density and aberrations</td>
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<td>Lunch</td>
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<tr>
<td>01:00 pm</td>
<td>New Directions @ FACET-II</td>
<td>High Field QED enabled by 100TW + 15GeV</td>
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<td>02:00 pm</td>
<td>New Directions @ FACET-II</td>
<td>High Fields: compressed 10GeV+300MeV—&gt; 100GeV/100GeV</td>
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<tr>
<td>02:30 pm</td>
<td>New Directions @ FACET-II</td>
<td>High Fields: computational challenges</td>
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<td>Laser upgrade options: &gt;100TW, transport and quality improvement</td>
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<td>Laboratory Astrophysics studies with electron-positron beams at FACET-II</td>
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<td>New Directions @ FACET-II</td>
<td>Material studies with compressed electron &amp; positron beams at FACET-II</td>
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<tr>
<td>04:45 pm</td>
<td>New Directions @ FACET-II</td>
<td>Atomic Physics with fast switching fields</td>
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<tr>
<td>05:15 pm</td>
<td>New Directions @ FACET-II</td>
<td>Discussions</td>
</tr>
<tr>
<td>05:45 pm</td>
<td>Adjourn</td>
<td></td>
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</table>
Phase-contrast images of probe profile...

20 GeV e-bunch

Composite 800nm pulse

Lithium plasma oven 1.5m

Probe angle about 0.01rad

Object plane

CCD

Probe imaging

Self-focusing, with not much deposited energy

Hot Plasma

Beam direction
Evolution of e-beam Ionized and Heated Plasma

Plasma channel evolution at FACET with 100ps step

Energy deposition in plasma column is a concern for colliders at very high rep rates
Concepts for Novel Beam Diagnostics at FACET-II

Interference of Dipole Edge Radiation – Monitor for Beam Divergence
- Fringe visibility depends on beam divergence and emittance
- Tested with ~1μm emittance and 60 MeV at BNL ATF

Betatron Radiation for Measuring Ultra-low Emittance
- Central betatron wavelength proportional to beam energy
- Linewidth of the radiation proportional to beam emittance

Quadrant EOS to Measure r-t Beam Correlations
- Goal is to measure correlation along ~1ps long bunch
- Spectrally encoded EOS with imaging spectrometer enable non-destructive measurement of correlations

Bunch Length Monitor for 3-30fs Long Bunches
- Laser light resonantly pumps gas to excited state
- Relaxation to intermediate state triggered by beam field
- Emission rate from intermediate to ground state depends on temporal spectrum of the beam field

Unprecedented beams at FACET-II provide exciting diagnostic challenges
Conclusion

FACET-II will deliver unprecedented high density electron beams for advanced accelerator R&D and broader community
  • Beam delivery is expected to start at the end of FY2019

FACET-II will operate as a National User Facility
  • FACET-II Science Workshop Oct. 17-20, 2017

Extreme fields generated with electron bunches offer alternative to lasers and can eventually enable studies of $\alpha \chi^{2/3} \approx 1$ regime