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

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September 5, 2017

ExHILP 2017

FACET·II
Facility for Advanced Accelerator Experimental Tests

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

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

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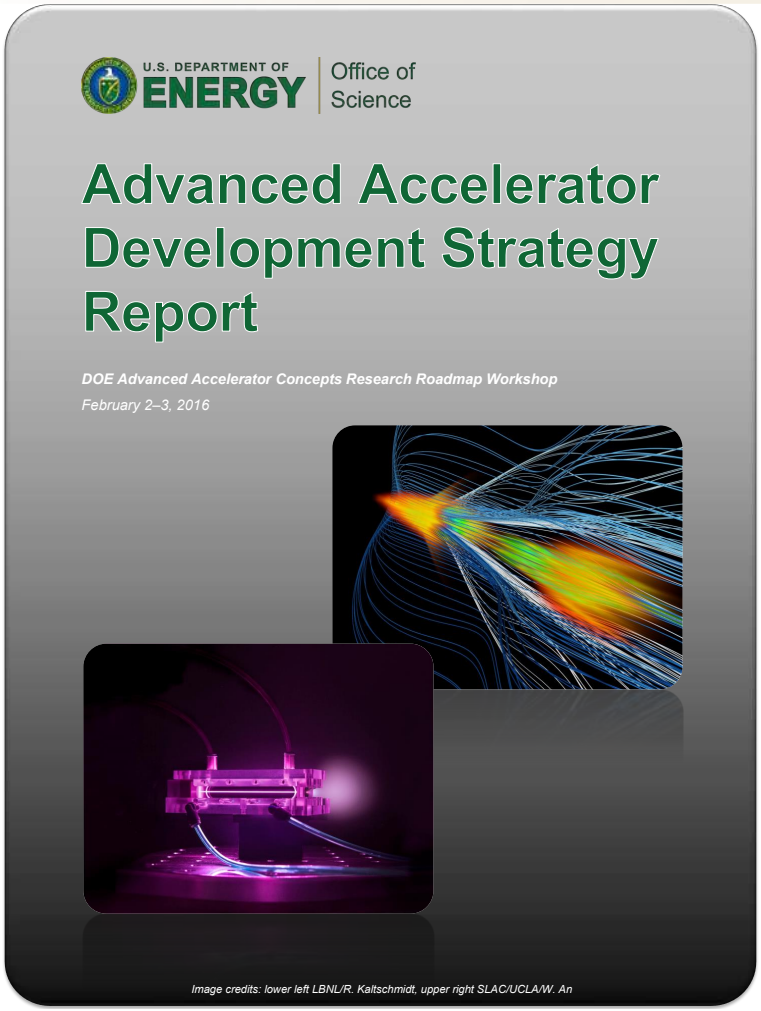
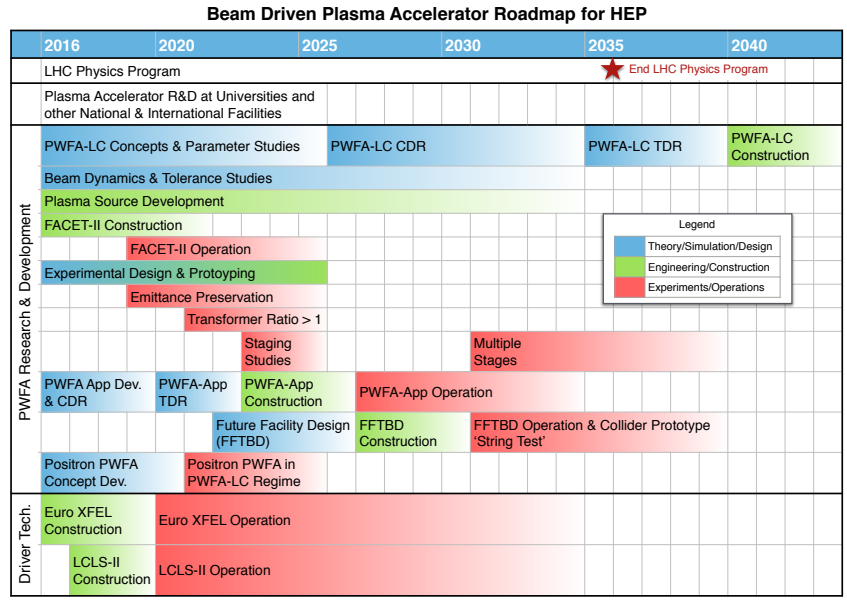


http://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Advanced_Accelerator_Development_Strategy_Report.pdf



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:

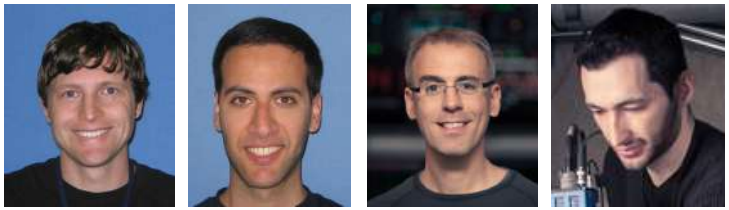
✓Mono-energetic e- acceleration

✓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)

Four researchers became professors:



FACET-II Timeline:

✓**Nov. 2013, FACET-II proposal, Comparative review**

✓**CD-0 Aug., 2015**

✓**CD-1 Review Oct., 2015**

✓CD-2/3A Aug. 2016

- CD-4 2022

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

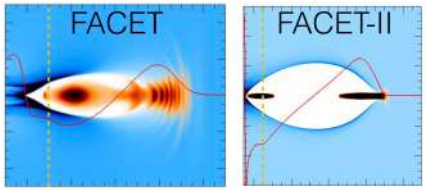
PWFA Research Priorities at FACET-II

Emittance Preservation with Efficient Acceleration

FY19-21

- High-gradient high-efficiency (instantaneous) acceleration has been demonstrated @ FACET

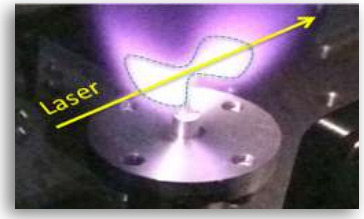
- Full pump depletion and preservation of emittance at μm level is planned as the first high impact experiment

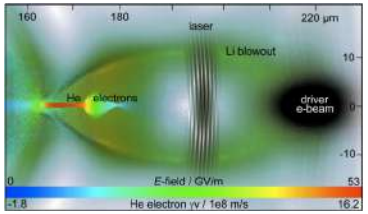


High Brightness Beam Generation & Characterization

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

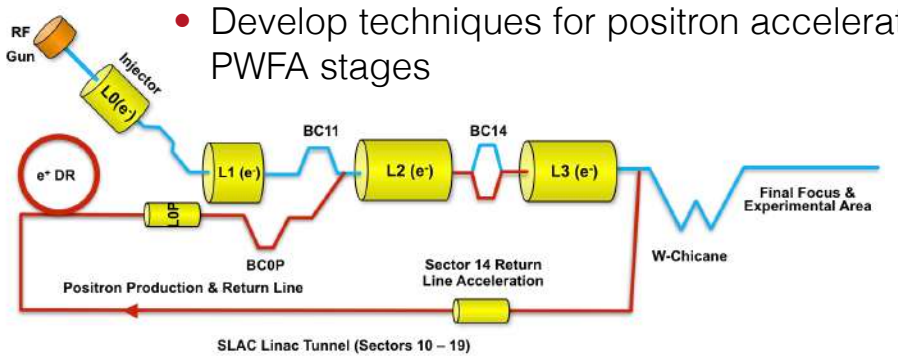




Positron Acceleration

FY21-24

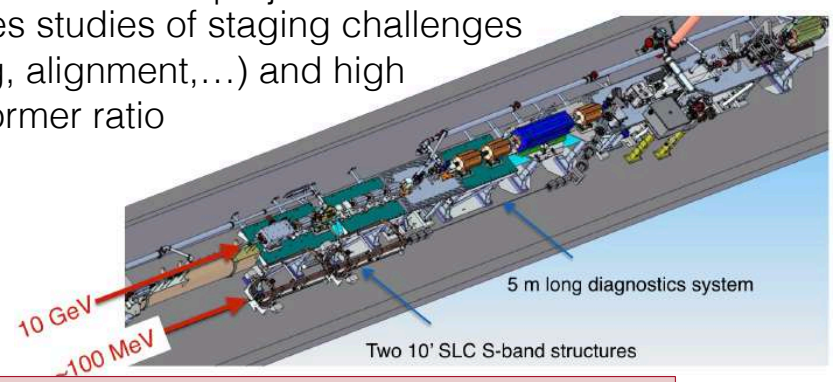
- Only positron capability in the world for PWFA research will be enabled by Phase II
  - Develop techniques for positron acceleration in PWFA stages



Staging Studies

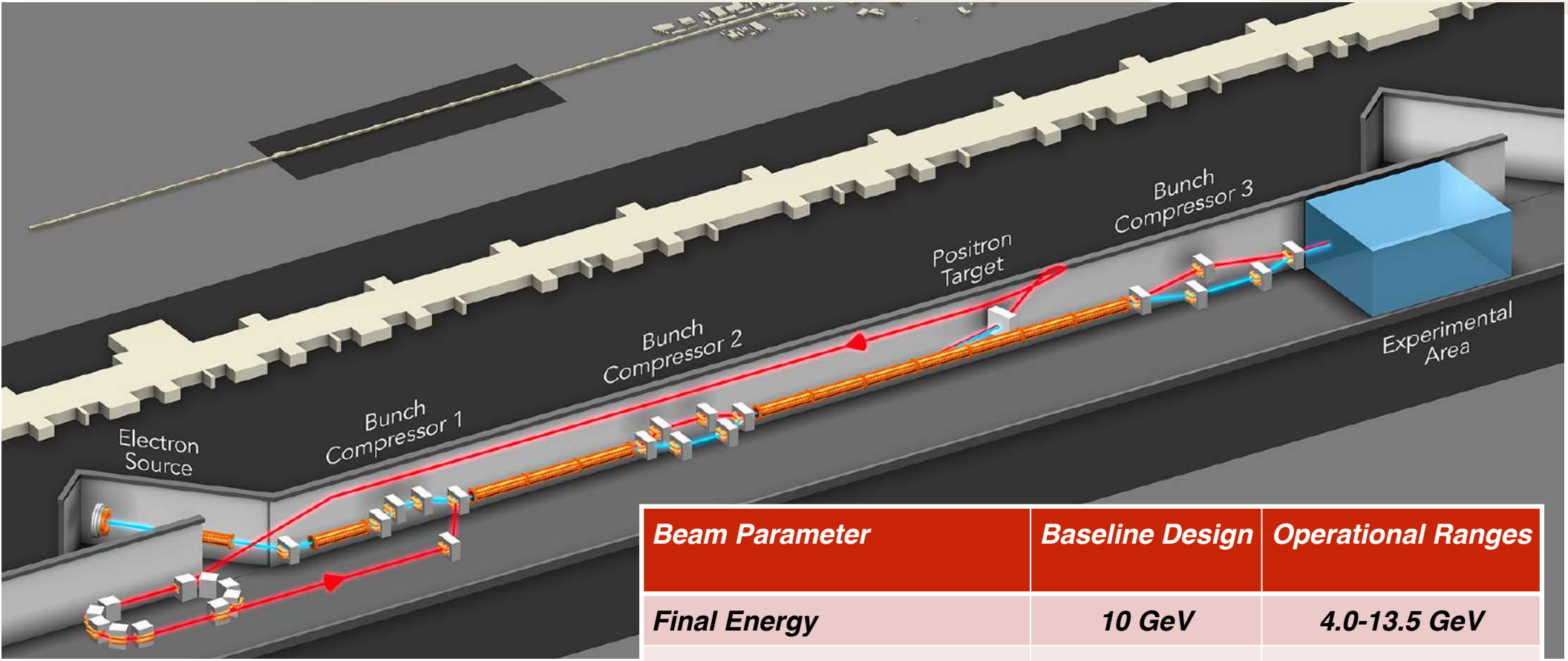
FY22-25

- 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



Broad User community is engaged in FACET-II Science Program Planning with Workshops: Oct. 12-16, 2015, Oct. 17-19 2016, Oct. 2017

FACET-II Layout and Beams

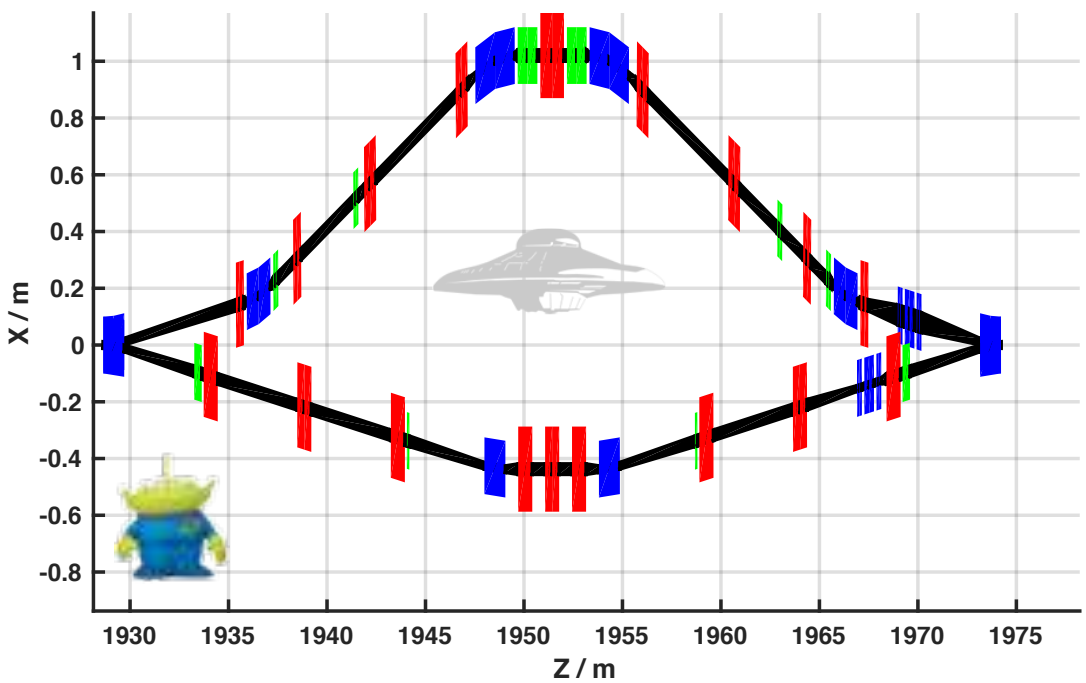


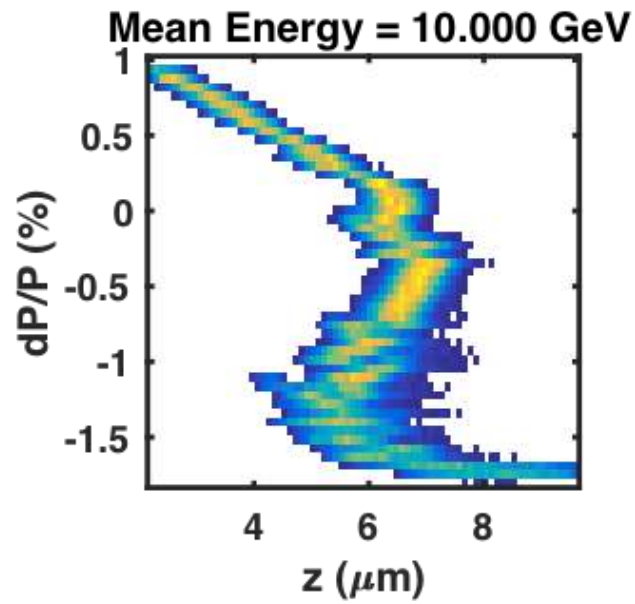
Beam Parameter	Baseline Design	Operational Ranges
Final Energy	10 GeV	4.0-13.5 GeV
Charge per pulse	2 nC	0.7-5 nC
Repetition Rate	30 Hz	1-30 Hz
Norm. Emittance $\gamma\varepsilon_{x,y}$ at S19	4.4, 3.2 μm-rad	3-6 μm-rad
Spot Size at IP $\sigma_{x,y}$	18, 12 μm	5-20 μm
Min. Bunch Length σ_z (rms)	1.8 μm	0.7-20 μm
Max. Peak current I_{pk}	72 kA	10-200 kA

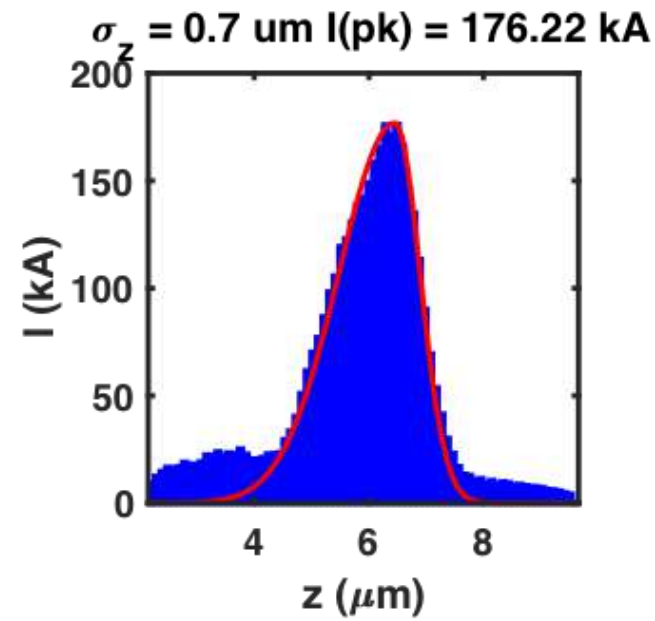
FACET-II Beam will Access New Regimes

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
- **~10^{12} V/cm** radial electric field (Es=1.3x10^{16} V/cm)
- **~10^{23} cm^{-3}** beam density
- **~10^{25} W/cm^2** peak intensity







Four Options to Study High Field QED at SLAC

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

χ ~0.3 ($\chi = E_p/E_s$)

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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

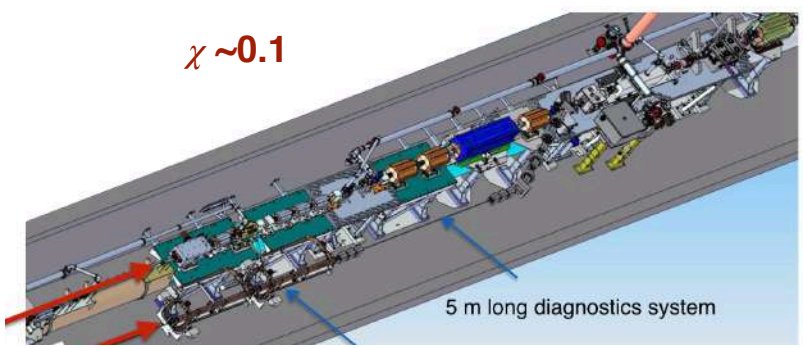
χ ~1-3

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

χ ~0.1



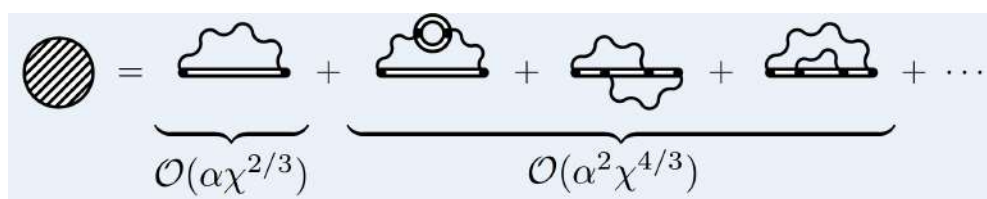
Option 4: 100GeV collider e-e+ with $\chi \approx 103$!

Future facility ~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)

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Beam field:

$\gamma \simeq 2\ 10^5$, $I_b = 10^6 A$, $\sigma_r = 10nm$, $\sigma_z = 100nm$

$$E_r = \frac{I_b/c}{2\pi\varepsilon_0\sigma_r} \simeq 6\cdot 10^{13}\, V/cm$$

$$\chi = 2\gamma\, E_r/E_s \simeq 1800$$

Field expansion parameter: *V.I. Ritus, ZhETF, Vol. 57, No. 6, p. 2176, 1970*

$$g = \alpha\,\chi^{2/3} \simeq 1$$

⇨ ***Perturbation theory does not work***
HEP in the presence of extreme field is unexplored

Beam disruption parameter

$$D = \frac{2 r_e N_e \sigma_z}{\gamma\,\sigma_r^{\,2}} \simeq 15$$

Beamstrahlung parameter *R.J. Noble, Nucl. Instrum. Methods Phys. Res. A 256 (1987) 427*

$$\Upsilon = \frac{5}{6}\frac{r_e^{\,2} N_e \gamma}{\alpha(\sigma_x + \sigma_y)\sigma_z} \simeq 10^3$$

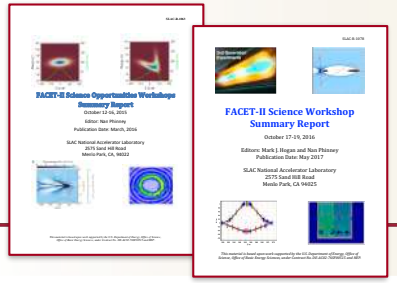
Average energy loss in quantum regime $(\Upsilon > 100)$

$$\delta = \frac{6}{5\sqrt{\pi}}\frac{\alpha\,\sigma_z}{\gamma\,\lambda\!\!\!^{-}_c} \simeq 3$$

P. Chen and V. Telnov, Phys. Rev. Lett. 63, 1796 (1989)

Probe beam sees beam density: $n_b = \dfrac{N_e}{(2\pi)^{2/3}\sigma_r^{\,2}\dfrac{\sigma_z}{\gamma}} \simeq 10^{31} cm^{-3}$

$$\frac{2}{\lambda\!\!\!^{-}_c{}^{3}} \simeq 3\cdot 10^{31} cm^{-3}$$



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FACET-II Science Workshop 2017

HOME | AGENDA | REGISTRATION | PARTICIPANTS | VISITING SLAC | CONTACT US

17-20 October 2017
hogan@slac.stanford.edu
http://conf.slac.stanford.edu/facet-2-2017

17-20 October 2017, Kavli Auditorium, SLAC

Agenda

Tuesday | Wednesday | Thursday | Friday

Start Time	Session Topic	Presentation	Presenter	Affiliation
09:00 am	Simulation Codes	QuickPIC	Weiming An	UCLA
09:30 am	Simulation Codes	OSIRIS	Warren Mori	UCLA
10:00 am	Simulation Codes	WarpX & Exascale	Jean LucVay	LBNL
10:30 am		**Coffee Break**		
11:00 am	Simulation Codes	VSIM	John Cary	UC Boulder & TechX
11:30 am	Simulation Codes	8 Years of Beam-Driven Wakefield Simulation -- lessons learned, reduced models, and future plans	David Bruhwiler	Radiasoft
12:00 pm	New Directions @ FACET-II	Active plasma lenses – limitations on beam energy/density and aberrations	Jan-Hendrik Röckeman	DESY
12:30 pm		**Lunch**		
01:30 pm	New Directions @ FACET-II	High Field QED enabled by 100TW + 15GeV	David Reis	SLAC
02:00 pm	New Directions @ FACET-II	High Fields: compressed 10GeV+300MeV—> 100GeV/100GeV	Sebastian Meuren	Max Planck Institute for Nuclear Physics
02:30 pm	New Directions @ FACET-II	High Fields: computational challenges	Thomas Grismayer	IST
03:00 pm		**Coffee Break**		
03:15 pm	New Directions @ FACET-II	Laser upgrade options: >100TW, transport and quality improvement	Alan Fry	SLAC
03:45 pm	New Directions @ FACET-II	Laboratory Astrophysics studies with electron-positron beams at FACET-II	Frederico Fiuza	SLAC
04:15 pm	New Directions @ FACET-II	Material studies with compressed electron & positron beams at FACET-II	Ioan Tudosa	University of Pennsylvania
04:45 pm	New Directions @ FACET-II	Atomic Physics with fast switching fields	TBD	
05:15 pm	New Directions @ FACET-II	Discussions		
05:45 pm		**Adjourn**		

QUICK LINKS

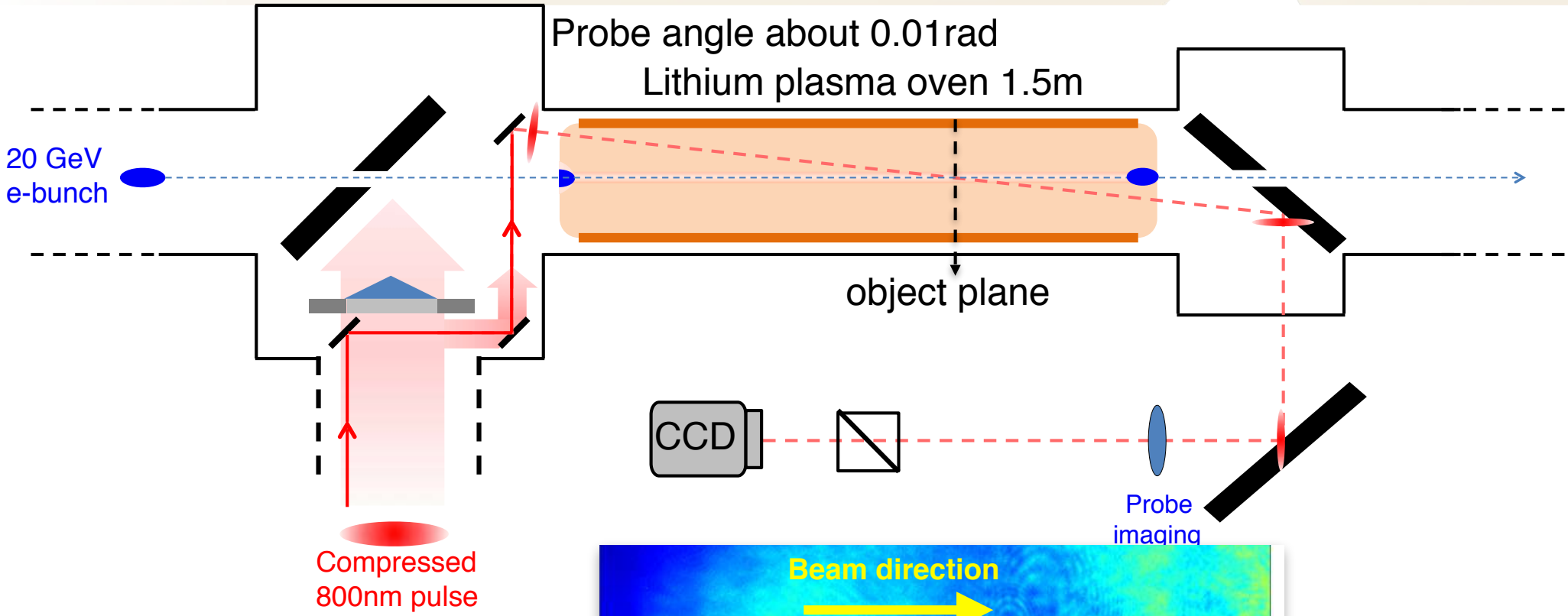
- Registration
- Agenda
- List of Participants
- FACET-II CDR
- FACET-II TDR
- 2016 Science Workshop
- 2016 Workshop Report
- 2015 Science Workshop
- 2015 Workshop Report

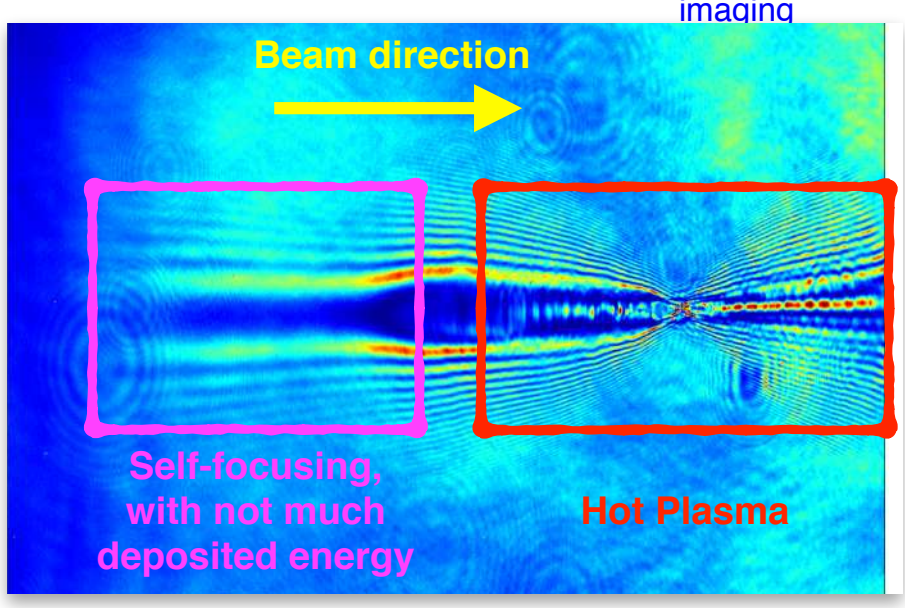
ACCOMMODATIONS

If you wish to reserve a room at the Stanford Guest House, please contact the Stanford Guest House directly at **(650) 926-2800** or reserve room via their **online booking system**.

Plasma Imaging

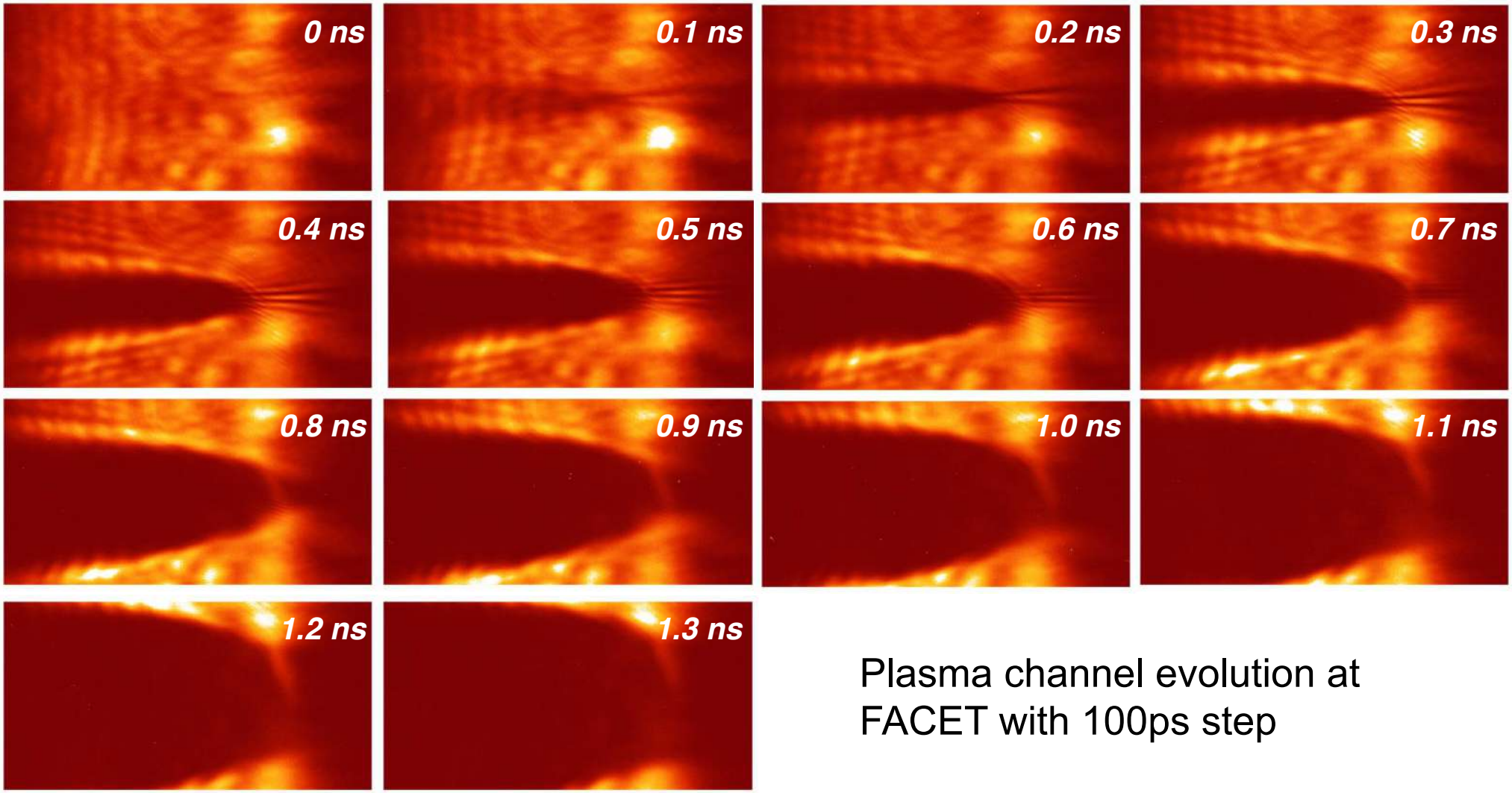
in Collaboration with M. Downer





Phase-contrast images of probe profile…

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

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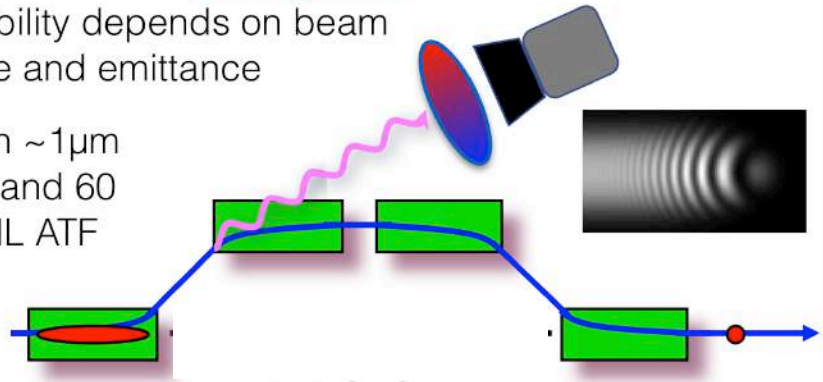
Interference of Dipole Edge Radiation – Monitor for Beam Divergence

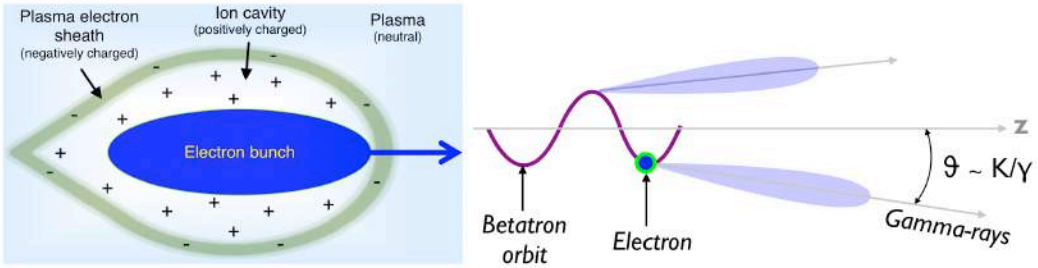
- Fringe visibility depends on beam divergence and emittance
- Tested with ~1μm emittance and 60 MeV at BNL ATF



O. Chubar PhD thesis 1990

Betatron Radiation for Measuring Ultra-low Emittance

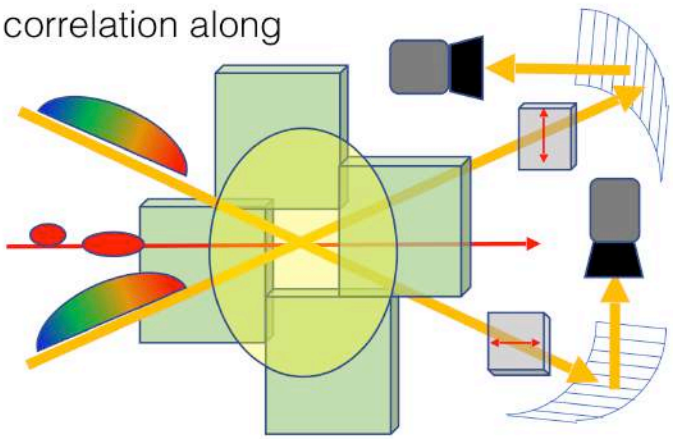
- Central betatron wavelength proportional to beam energy
- Linewidth of the radiation proportional to beam emittance



J. Rosenzweig, 2016 FACET-II Science Workshop

Quadrant EOS to Measure r-t Beam Correlations

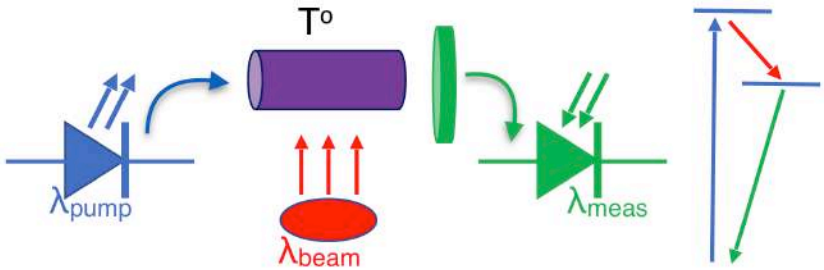
- Goal is to measure correlation along ~1ps long bunch
- Spectrally encoded EOS with imaging spectrometer enable non-destructive measurement of correlations



V. Yakimenko, Private comm.

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



M. Zolotorev, Private comm.

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

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