FACET-II Facility for Advanced Accelerator Experimental Tests

Plasma Wakefield Accelerator Science at FACET-II

4th European Advanced Accelerator Concepts Workshop

Mark J. Hogan

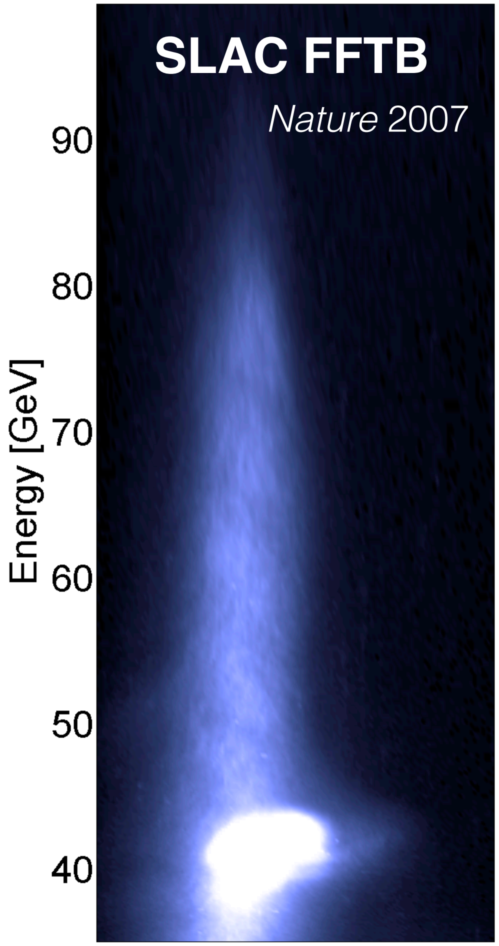
September 19, 2019

U.S. DEPARTMENT OF ENERGY
Office of Science

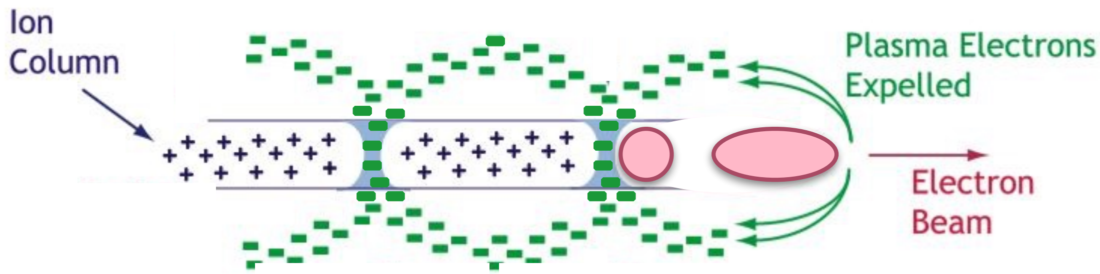
SLAC NATIONAL ACCELERATOR LABORATORY

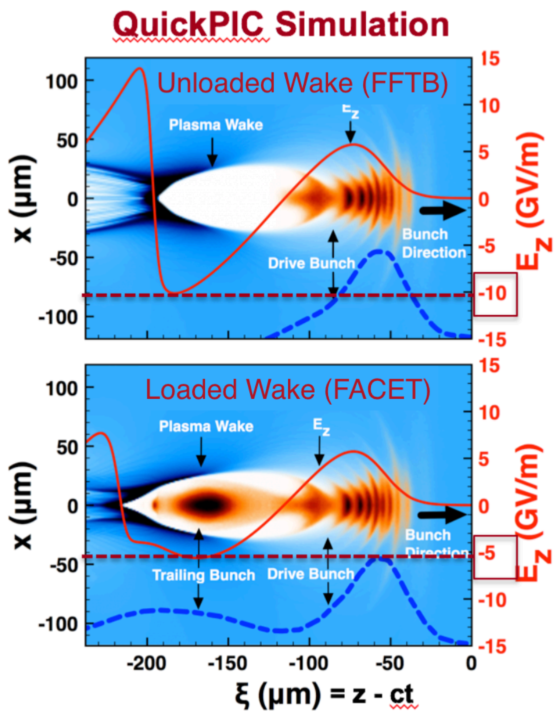
High-Efficiency Acceleration of an Electron Bunch in a Plasma Wakefield Accelerator

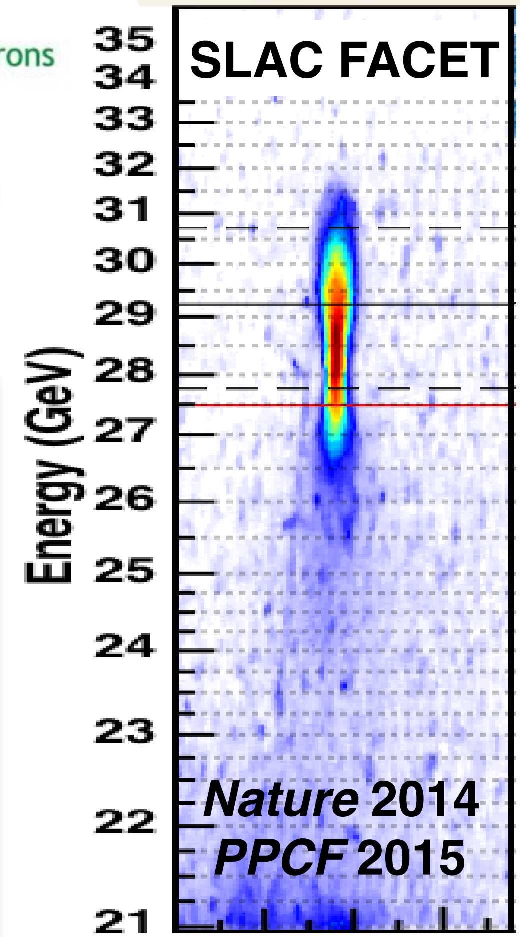
UCLA SLAC



43 GeV
Energy Gain



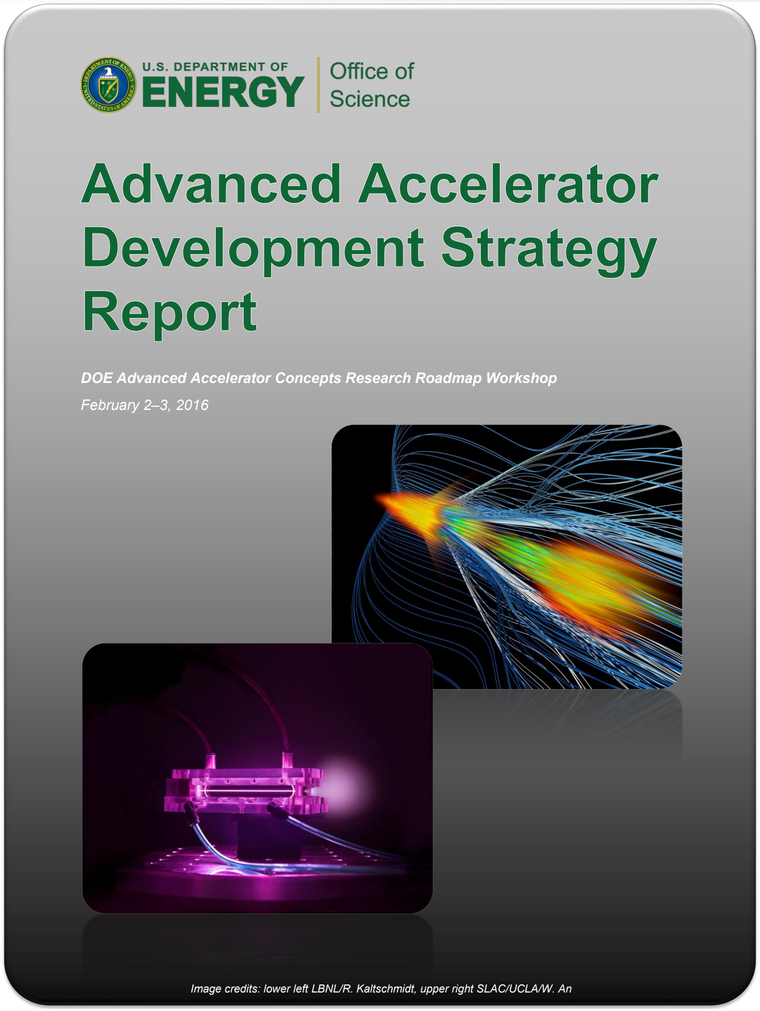




9 GeV
Energy Gain

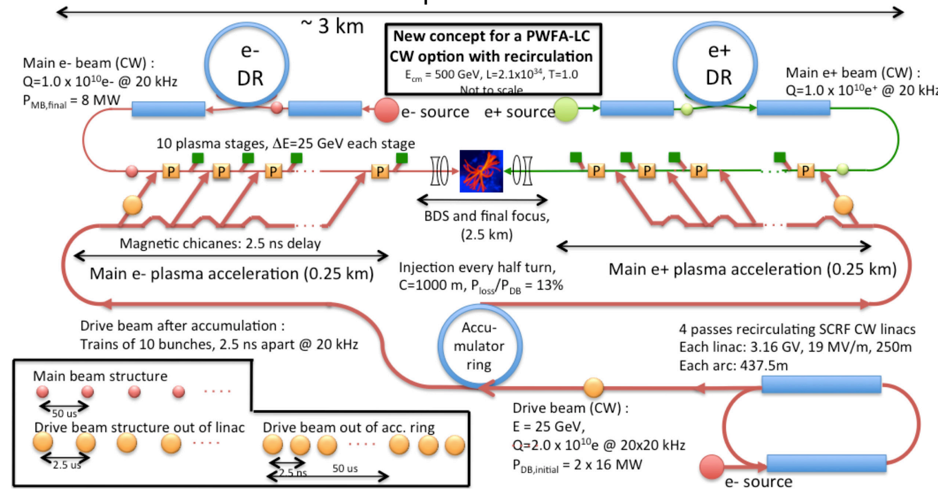
Narrow energy spread acceleration with high-efficiency has been demonstrated
FACET-II experiments will focus on simultaneously preserving beam emittance

PWFA Experimental Program at FACET-II is Motivated by Roadmap for Future Colliders Based on Advanced Accelerators



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

A Conceptual PWFA-LC



E. Adli et al., ArXiv 1308.1145
J. P. Delahaye et al., Proceedings of IPAC2014

Key elements for the next decade:

- Beam quality – focus on emittance preservation at progressively smaller values
- Positrons – use FACET-II positron beam identify optimum regime for positron PWFA
- Injection – ultra-high brightness sources, staging studies with external injectors

PWFA Experimental Program at FACET-II is Motivated by Roadmap for Future Colliders Based on Advanced Accelerators

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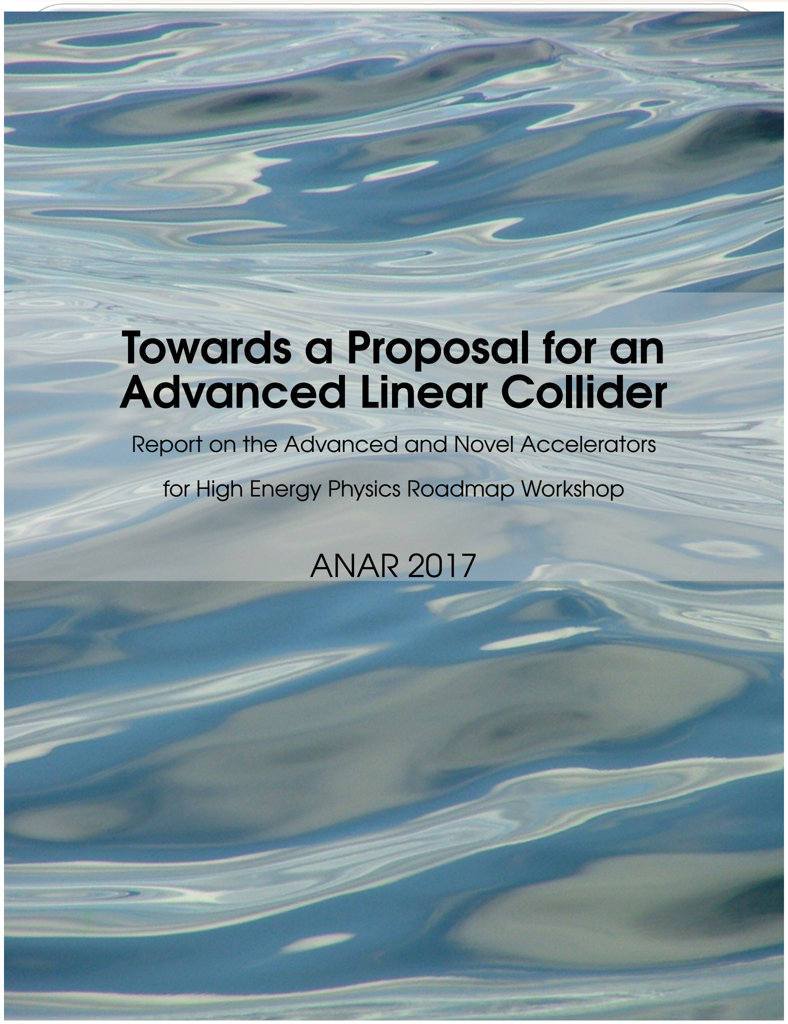

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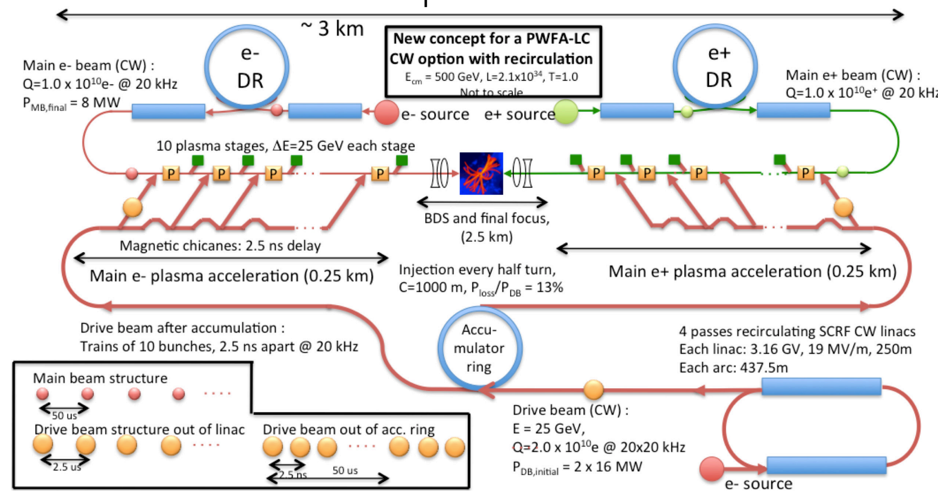

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FACET-II: A National User Facility Based on High-energy Beams and Their Interaction with Plasmas and Lasers

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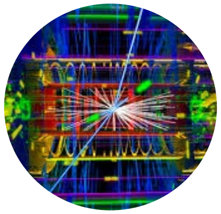
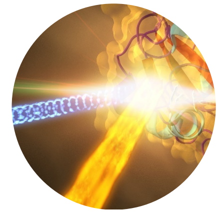


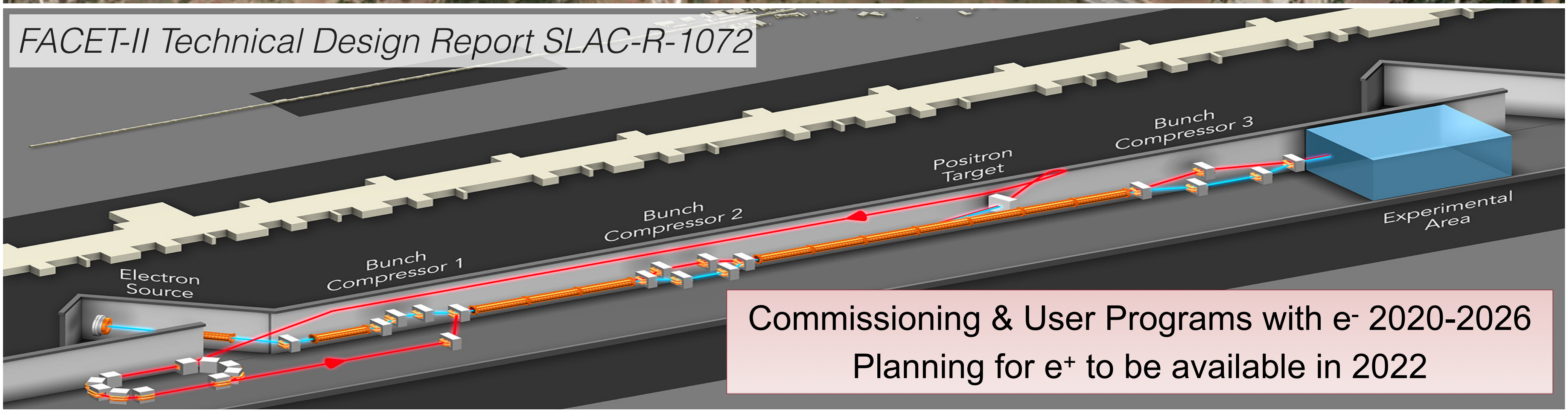
Advance the energy frontier for future colliders



Develop brighter X-rays for photon science

10 GeV e^- & e^+ beams, 2nC/1nC @ 30/5Hz, ~μm emittance, Ipk > 10kA

FACET-II Technical Design Report SLAC-R-1072



Commissioning & User Programs with e^- 2020-2026
Planning for e^+ to be available in 2022

FACET Experimental Ti-Sapph Laser Upgrades

Improved pointing stability

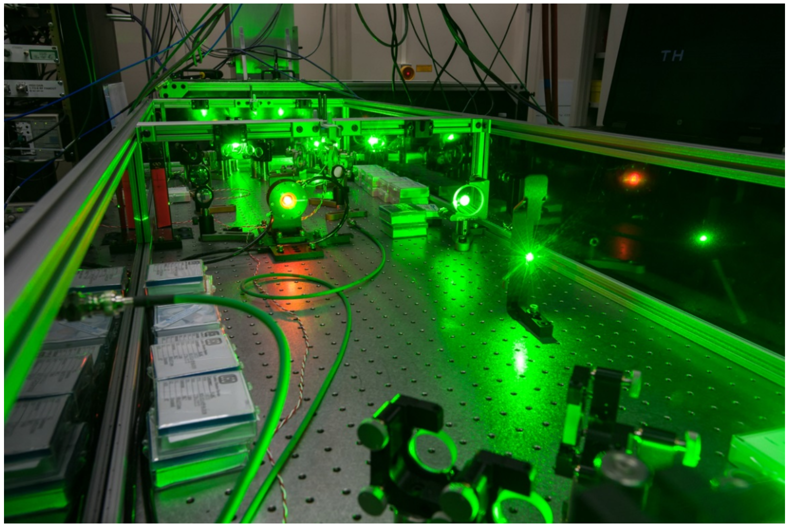
- ✓ Pointing diagnostics & feedbacks for experimental laser transport line
- Re-building problematic mounts
- Temperature control for transport system

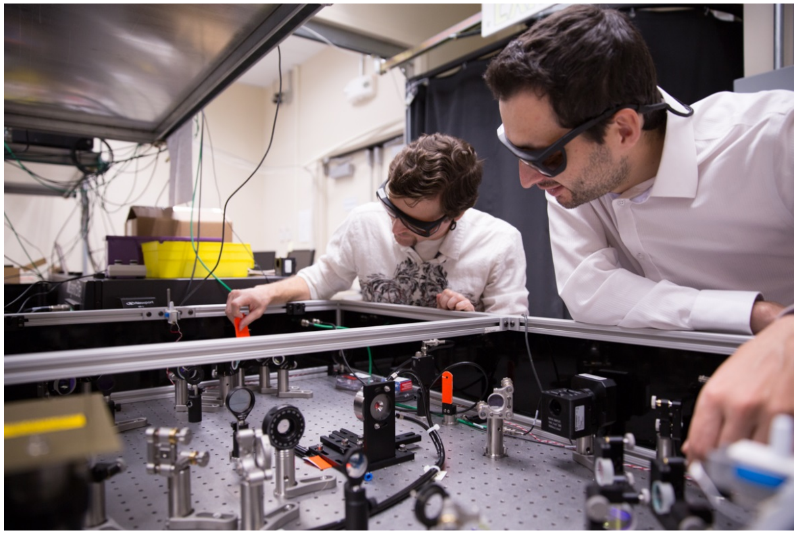
Improved mode quality in IP area

- ✓ Deformable mirror(s)

Higher Intensity

- ✓ Laser system will be upgraded to achieve >15TW at 10Hz (e.g. 0.6J/35fs)
- 100TW class upgrade possible at 'moderate' cost with upgrades to the laser, transport, and delivery systems





Design and operations support provided by experienced LCLS Laser Science & Technology Division

E-300: Energy Doubling of Narrow Energy Spread Witness Bunch while Preserving Emittance with a High Pump-to-Witness Energy Transfer Efficiency in a Plasma Wakefield Accelerator

Science deliverables:

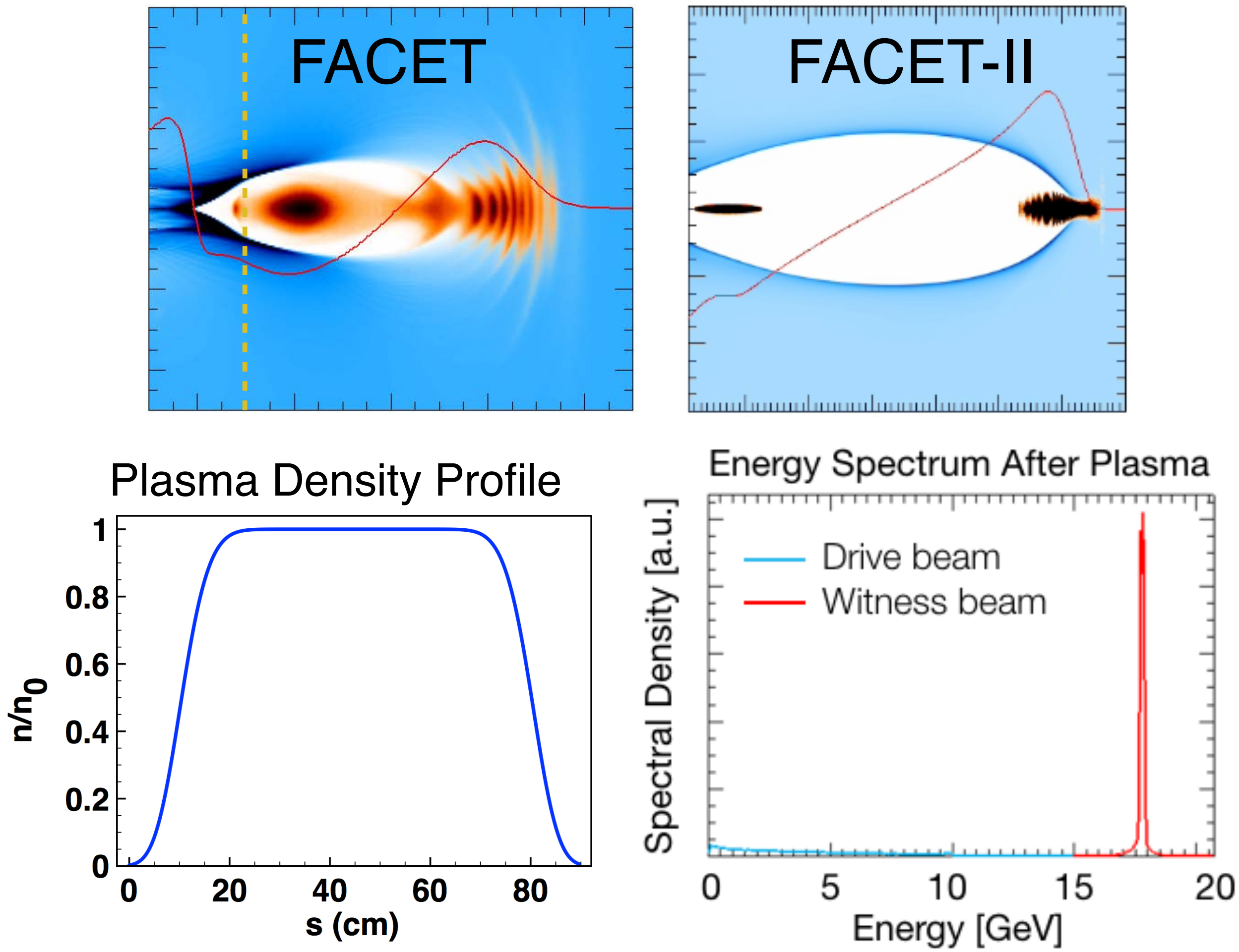
- Pump depletion of drive beam with high efficiency & low energy spread acceleration
- Beam matching and emittance preservation

Key upgrades:

- Photoinjector beam
- Matching to plasma ramps
- Differential pumping
- Single shot emittance diagnostic

Plasma source development:

- Between 10-20μm emittance, beam expected to ionize He in down ramp
- Next step laser ionized hydrogen source in development at CU Boulder

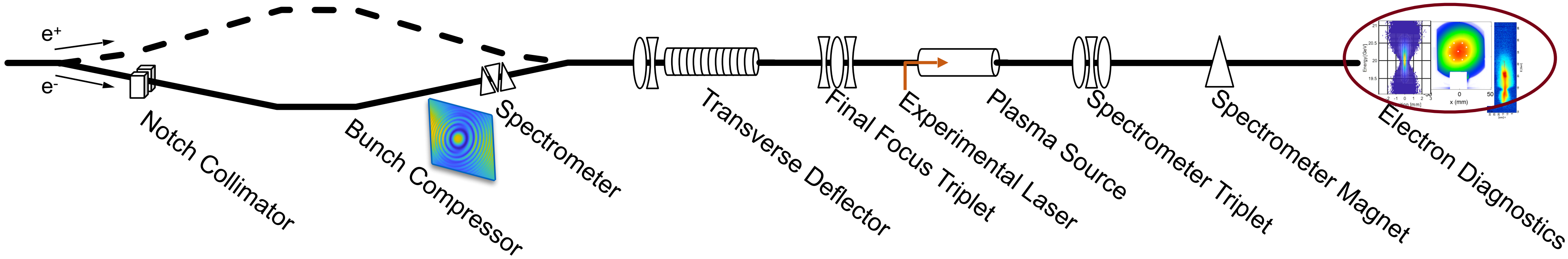


C Joshi et al 2018 Plasma Phys. Control. Fusion 60 034001

Flexibility of the photo-injector allows optimal beams for PWFA studies

Updated Electron and Betatron Radiation Diagnostics for Measuring Beams after PWFA

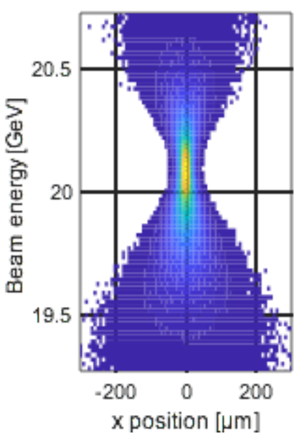
See presentation by Sebastien Corde WG1-5 M16:20

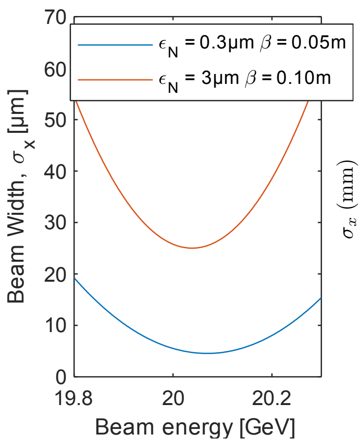


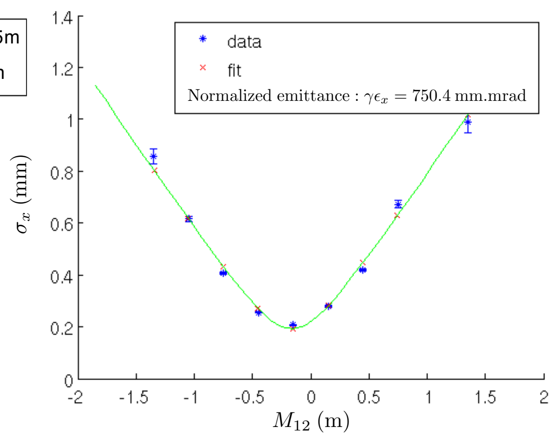
Electron Beam

Emittance:

- Edge radiation in bunch compressors
- High resolution in vacuum OTR in spectrometer for single shot butterfly or multi-shot dispersive quad scan

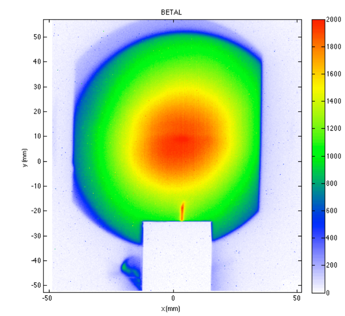




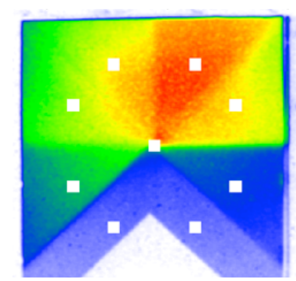


Gamma-rays

Angular distribution: convertor + scintillator, and pixelized CsI array for higher sensitivity



Spectrum: transverse array of filters/convertors
Ross filters (<100keV)
Step filters (up to 250keV)



Particle and Gamma-ray Working Group provides input to facilitate diagnostics that simultaneously benefit multiple experiments

FACET Experiments use different Plasmas: Laser or Beam Field Ionization, "Heat pipe oven" or Gas

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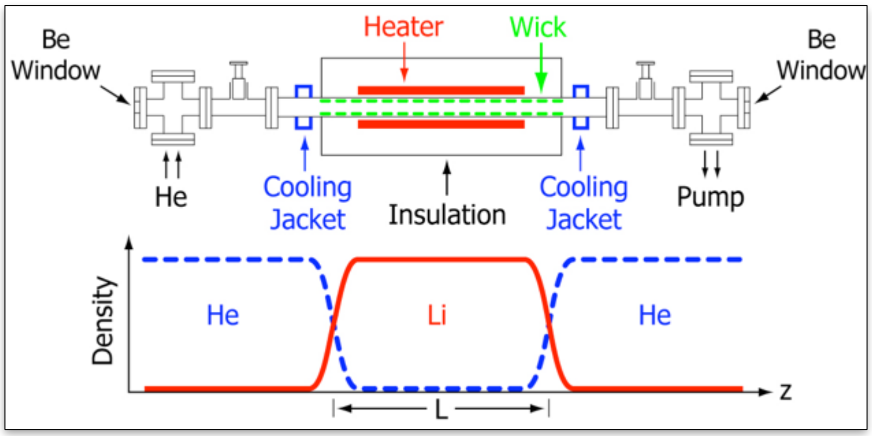
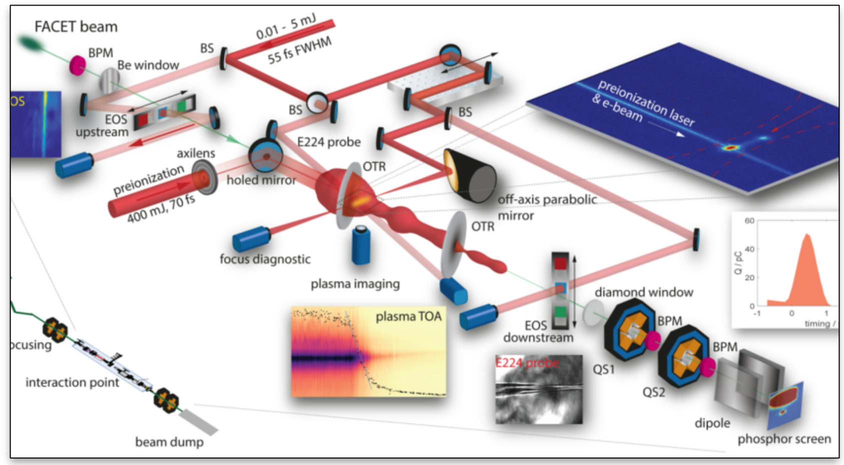
Heat Pipe Oven: Li/He or Rb/Ar Vapor/buffer gas (at same pressure):

- $n_0 = 10^{14}$-10^{17} e^-/cm^3, L = 20-200 cm



Hydrogen, Argon or Mixed Gas Cells:

- $n_0 = 10^{16}$-10^{18} e^-/cm^3, L = 10-100 cm



Enabled Many Advances in PWFA Physics:

• 42 GeV E-gain in one meter – ***Nature 2007***	***(2.7E17, 35 Torr)***
• High efficiency acceleration – ***Nature 2014***	***(5E16, 5.8 Torr)***
• Multi-GeV e+ PWFA – ***Nature 2015***	***(8E16, 9.6 Torr)***
• Hollow Channel e+ PWFA – ***Nature Communications 2016***	***(8E16, 9.6 Torr)***
• Wakefield Mapping – ***Nature Communications 2016***	***(2.5E17, 32.5 Torr)***
• Ionization Injection – ***PRL 2014***	***(2.7E17 Rb, 16 Torr)***
• High-field Acceleration – ***Nature Communications 2016***	***(1E18 Ar, 32 Torr)***
• Trojan-horse Injection – ***Nature Physics 2019***	***(1E17, 3.2 Torr H/He mix)***

FACET-II experiments will require new sources with additional flexibility and control

See presentation by Mike Litos WG5 W19:00

Beam Loading in Non-linear Wakes

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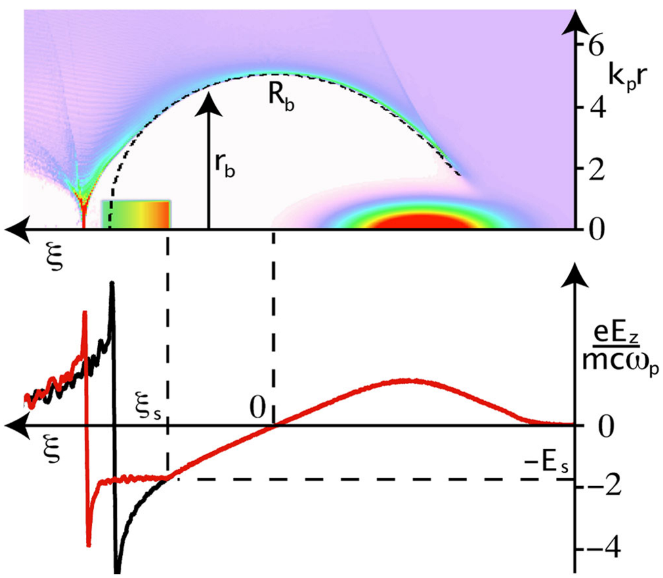
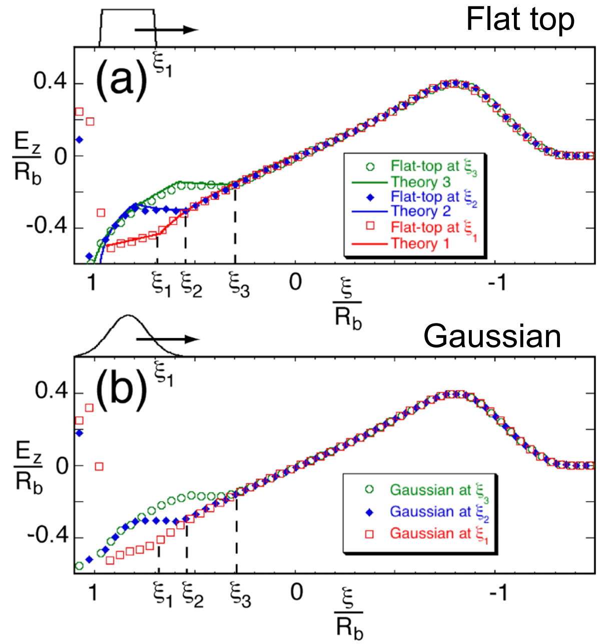
Theoretical framework, augmented by simulations, provides a recipe





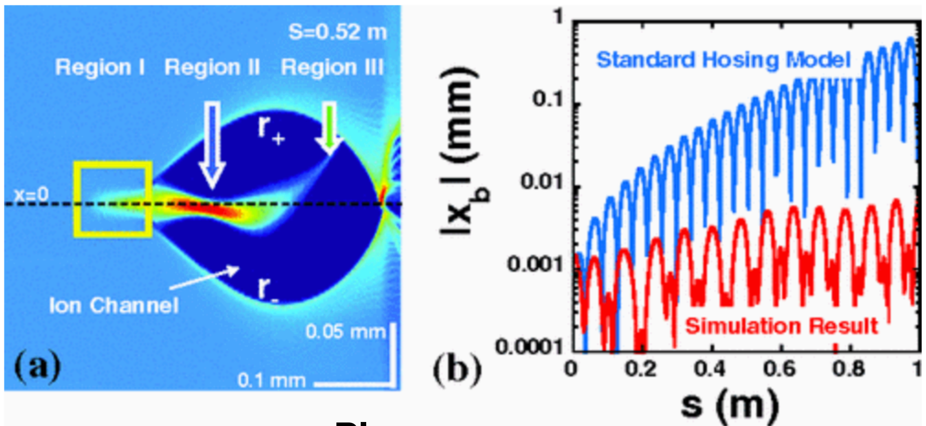
Roadmap emphasizes the need to answer the question: Is it possible to strongly load the longitudinal wake without strong transverse wakes and BBU?

- Relativistic Beams provide a non-evolving wake
- Possible to nearly flatten accelerating wake – even with Gaussian beams
- Gaussian beams provide a path towards $\Delta E/E \sim 10^{-2}$ - 10^{-3}
- Applications requiring narrower energy spread, higher efficiency or larger transformer ratio → Shaped Bunches

$$\mathcal{L} = \frac{P_b}{E_b}\left(\frac{N}{4\pi\sigma_x\sigma_y}\right)$$

See: M. Tzoufras et al, Phys. Plasmas ***16****, 056705 (2009); M. Tzoufras et al, Phys. Rev. Lett.* ***101****, 145002 (2008); W. Lu et al., Phys. Rev. Lett.* ***96****, 165002 (2006) and References therein*

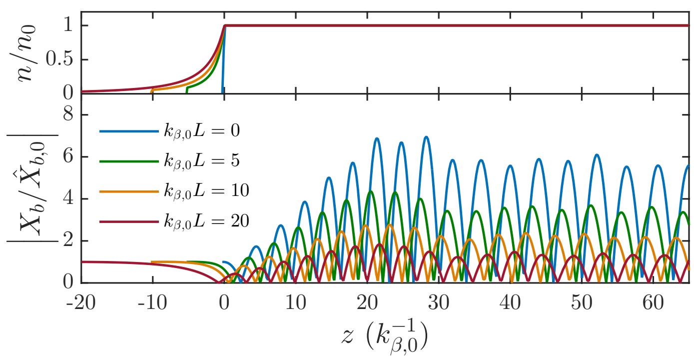
E-302: Transverse Wakefields and Instabilities in Plasma Wakefield Accelerators



Many **mechanisms of emittance growth** have been put forward, e.g. ion motion, hosing…

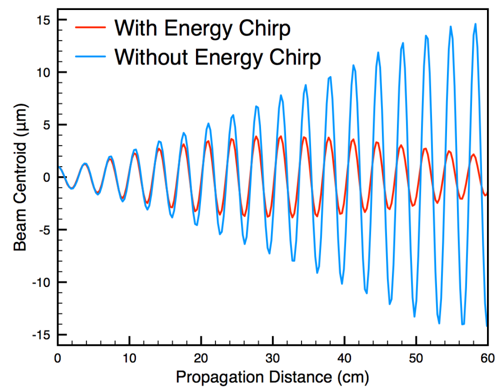
D. Whittum et al. PRL 67, 991 (1991) **LBNL/SLAC**
J. Rosenzweig et al., 95, 195002 (2005) **UCLA**
C. Huang et al., PRL 99, 255001 (2007) **UCLA**
V. Lebedev et al., PRST-AB 20, 121301 (2017) **FNAL**

Plamsa ramps

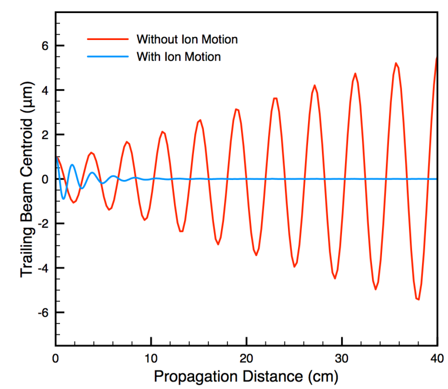


T. Mehrling et. al., PRL 118, 174801 (2017) **DESY/LBNL**

Energy Spread



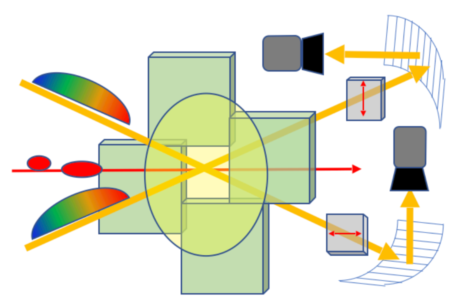
Ion Motion



W. An et al. PRL 118, 244801 (2017) **UCLA**

Proposed **techniques for mitigation** need to be tested experimentally

Quadrant EOS to measure r-t beam correlations



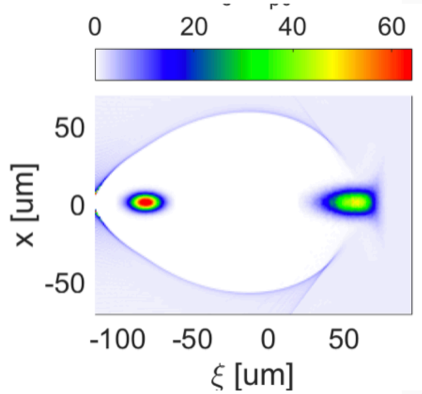
Goal is to measure correlation along ~1ps long bunch

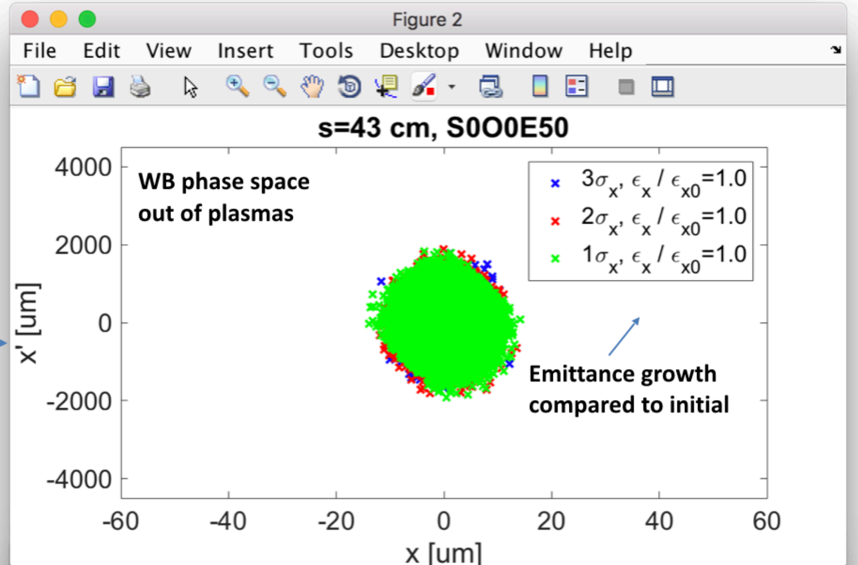
Benchmark theoretical and numerical predictions will be a strong component of FACET-II Program

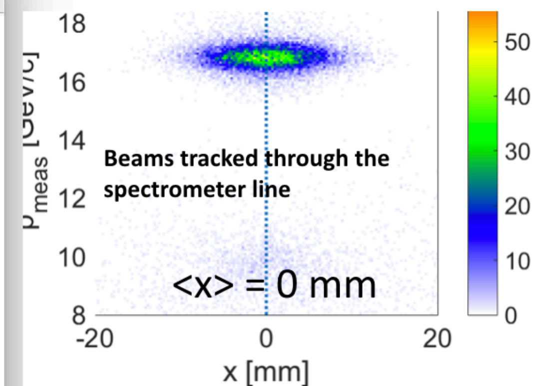
Instability Possibly Strong Enough to Measure – Need Good Diagnostics and Development of New Techniques

Observability in experiment:

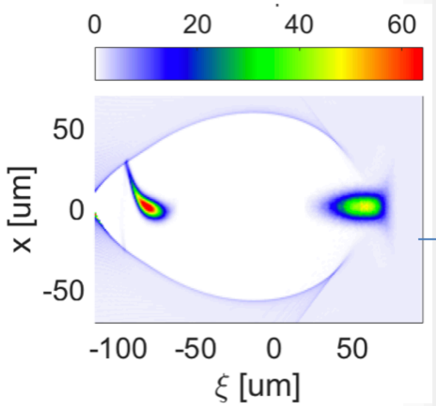
Case 1: On-axis MB

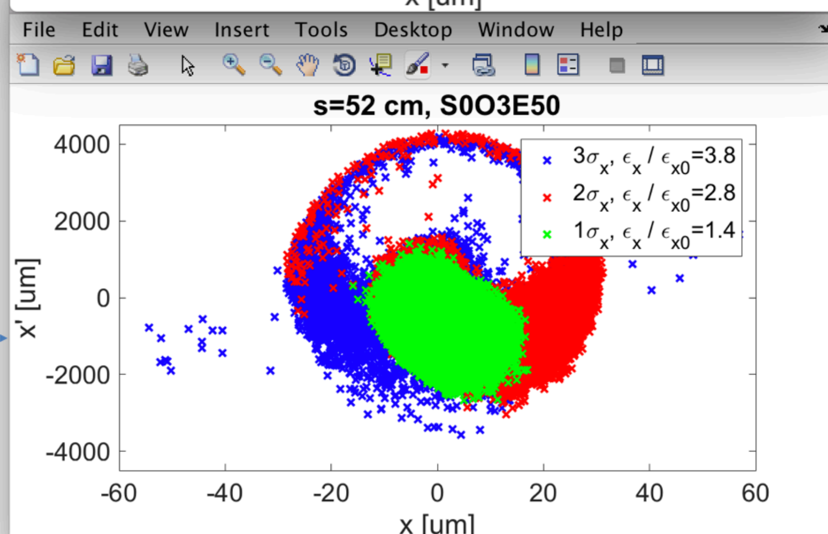


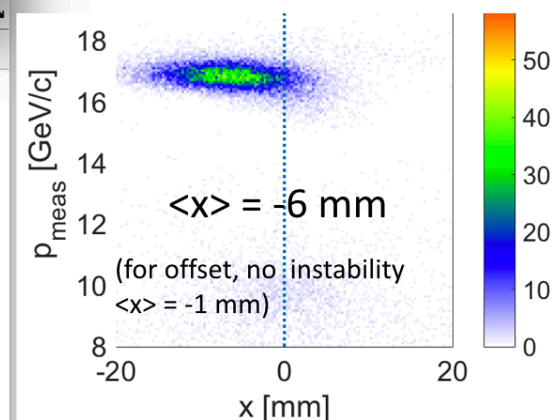




case 2: Off-axis MB







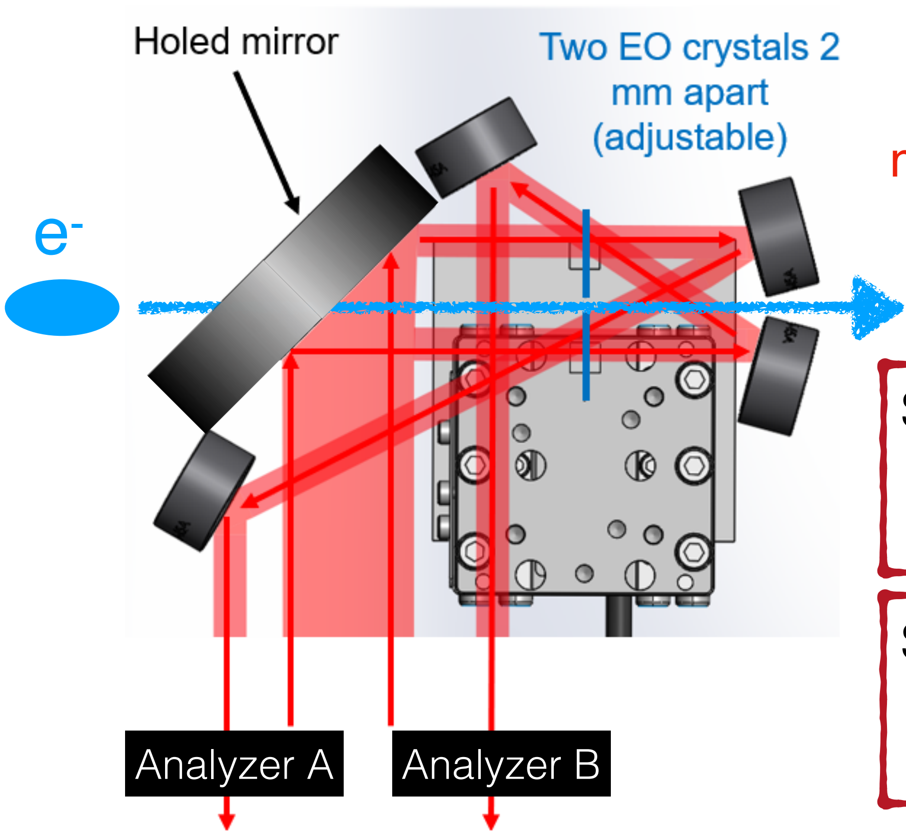
Observables:

- emittance
- spot sizes
- kicks
- as function of energy

A factor 3 of emittance growth for $2\sigma_z$ of beam is significant, but may be hard to distinguish from other sources (e.g. mismatch). Similar arguments situation for σ_x (directly observable on profile monitors)

Developing an EOS BPM for Transverse Wakefield Studies

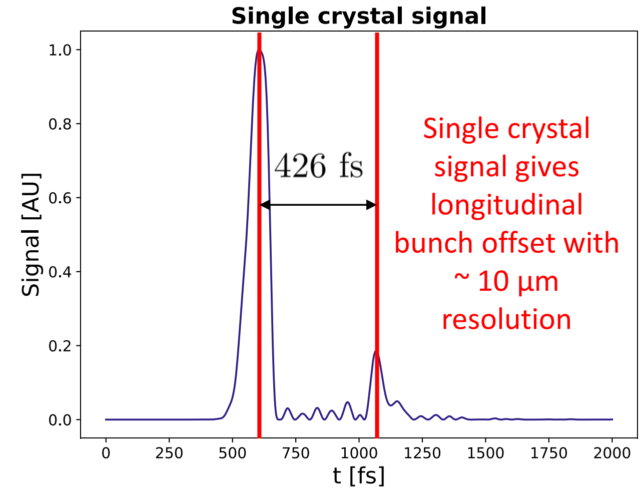
- Single crystals provide standard measurement of longitudinal spacing
- Difference signal provides horizontal offset
- First generation will measure one transverse direction
- Calibrated with stage translation

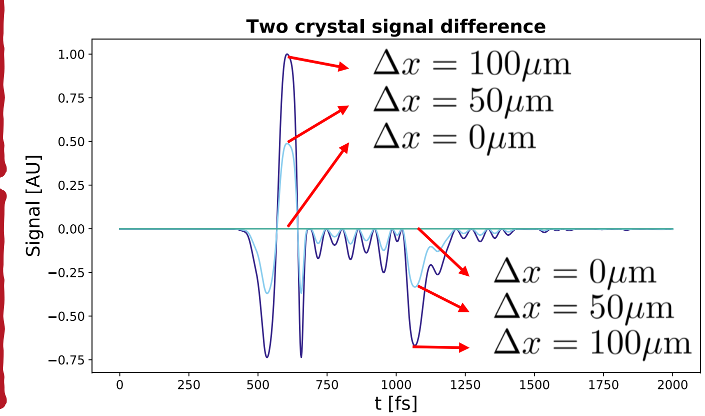


Signal difference of two EO crystals measures transverse offset with ~ 5μm resolution

See presentation by Keenan Hunt-Stone WG5 T18:20

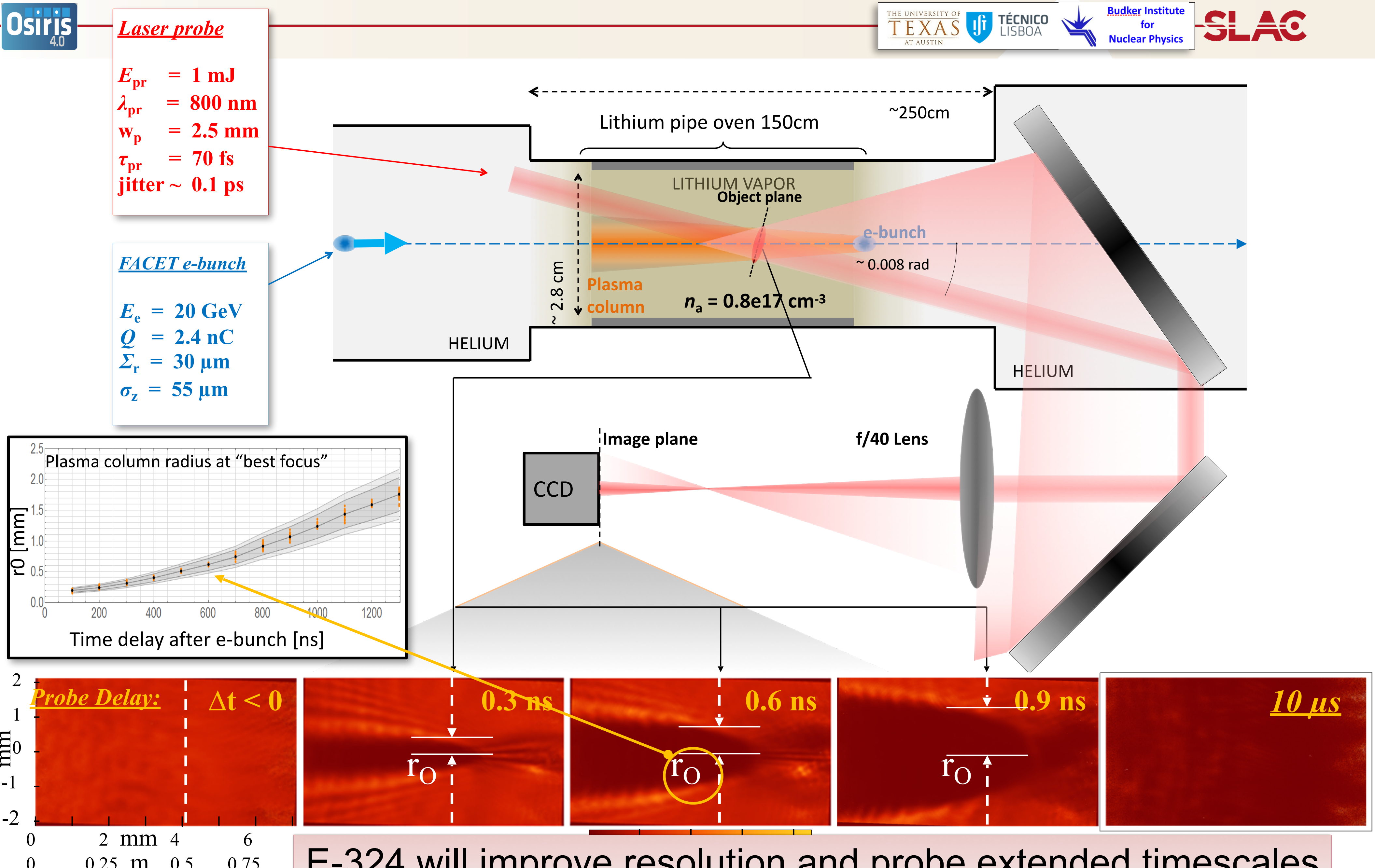
See presentation by Mark Hogan WG5 T16:40





Use single shot information to correlate emittance growth vs witness beam offset

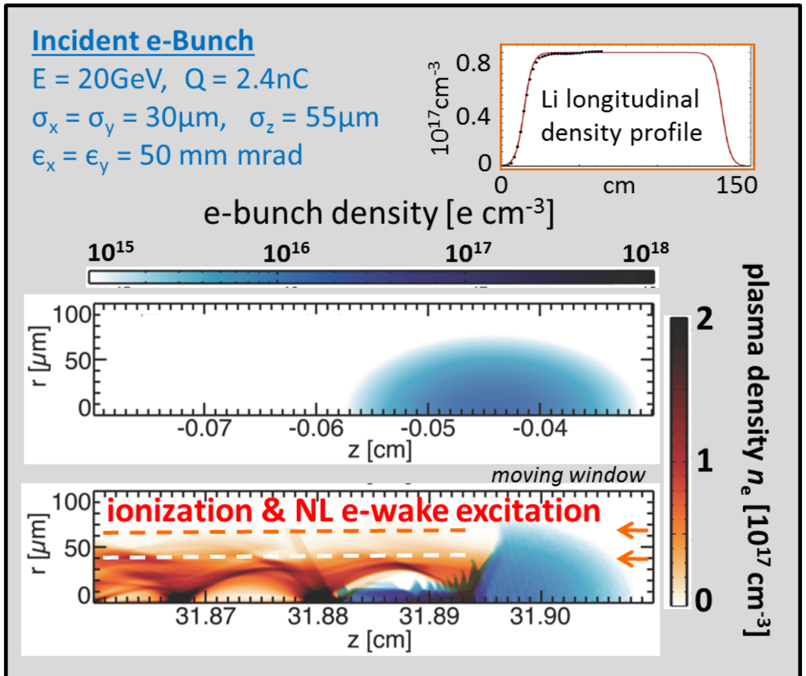
Optical Measurements of Nanosecond-scale Plasma Channel Evolution Excited by Beam-driven Plasma Wakes at FACET (E224)



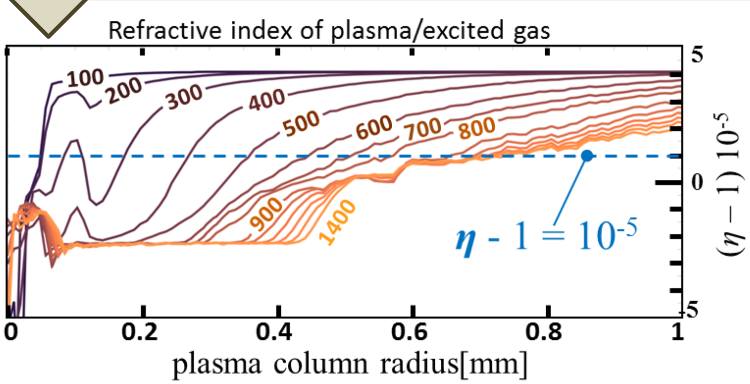
E-324 will improve resolution and probe extended timescales

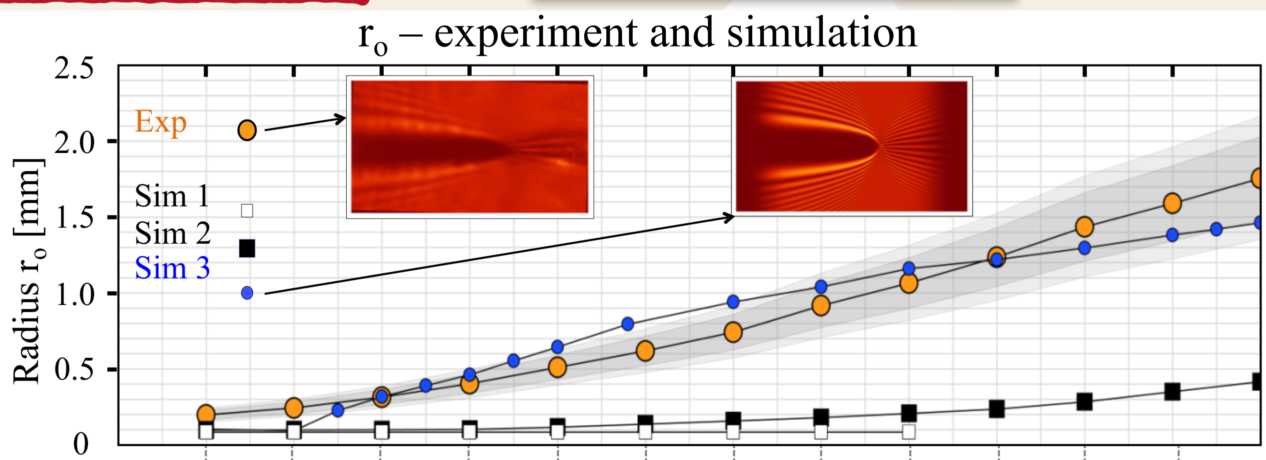
Optical Measurements of Nanosecond-scale Plasma Channel Evolution Excited by Beam-driven Plasma Wakes at FACET (E224)

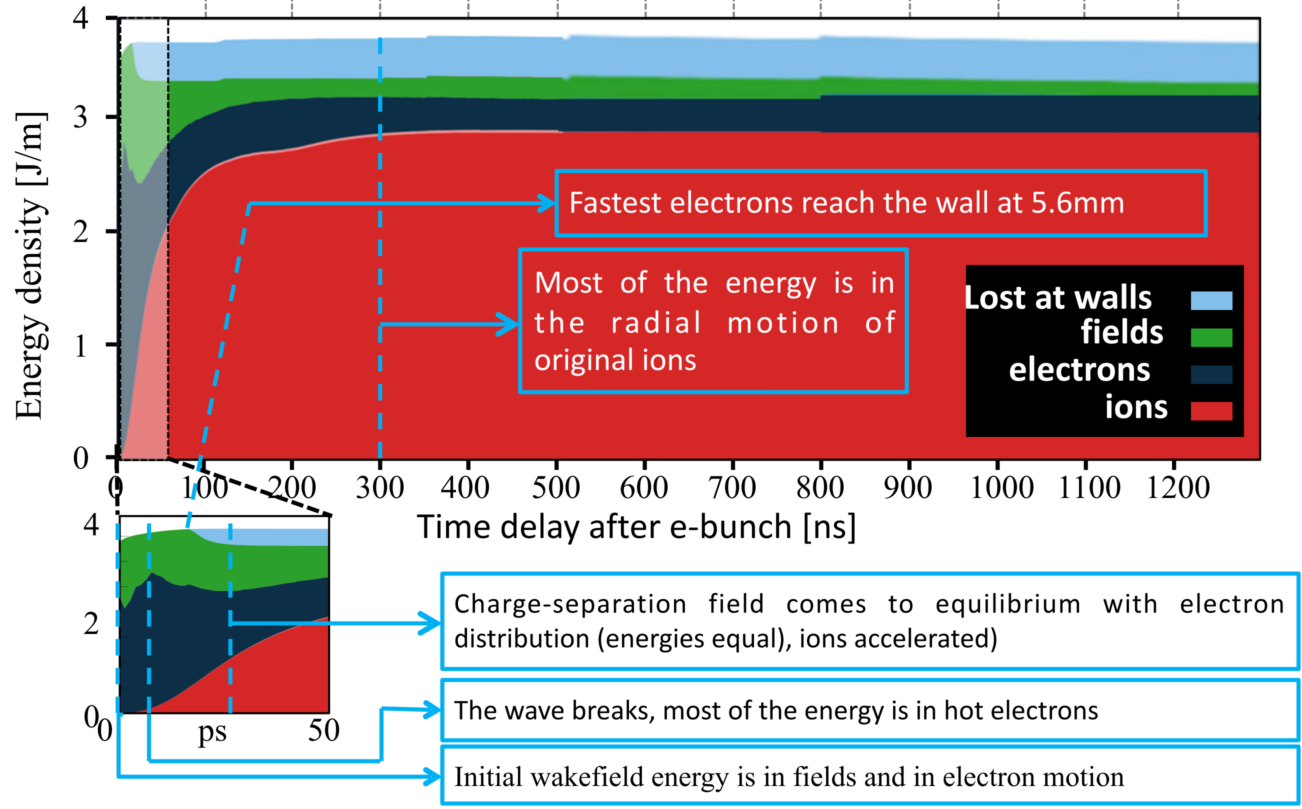
See poster by Konstantin Lotov Monday 17:00



Osiris results form the initial condition for the LCODE. LCODE simulation "3" Includes electron and ion impact ionization of neutral lithium, and also excitation dynamics.







Development of High-Brightness Electron Sources

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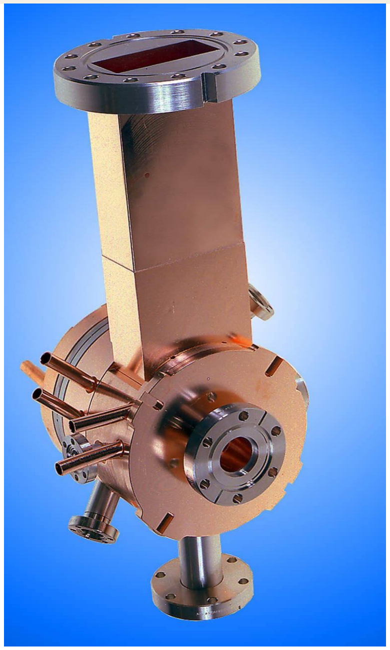
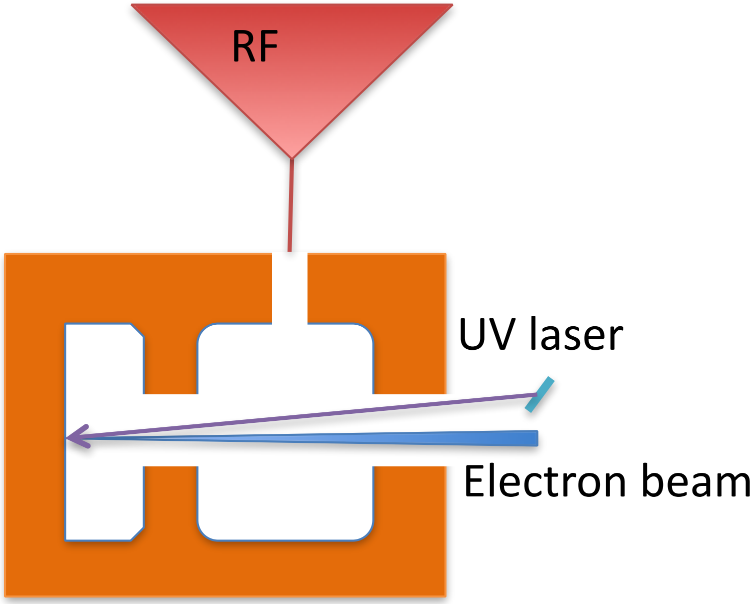
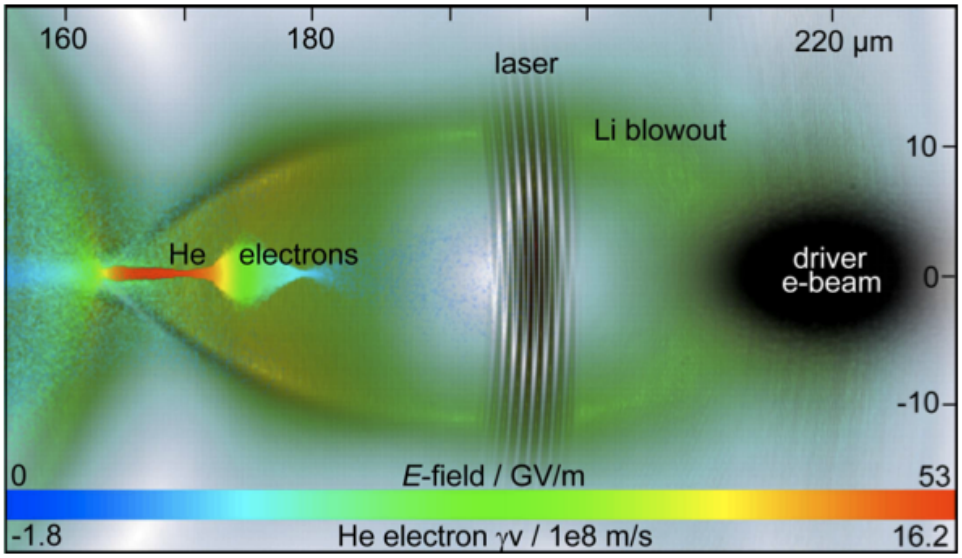
LCLS Style Photoinjector

- 100MeV/m field on cathode
- Laser triggered release
- ps beams - multi-stage compressions & acceleration
  - Tricky to maintain beam quality (CSR, microbunching…)







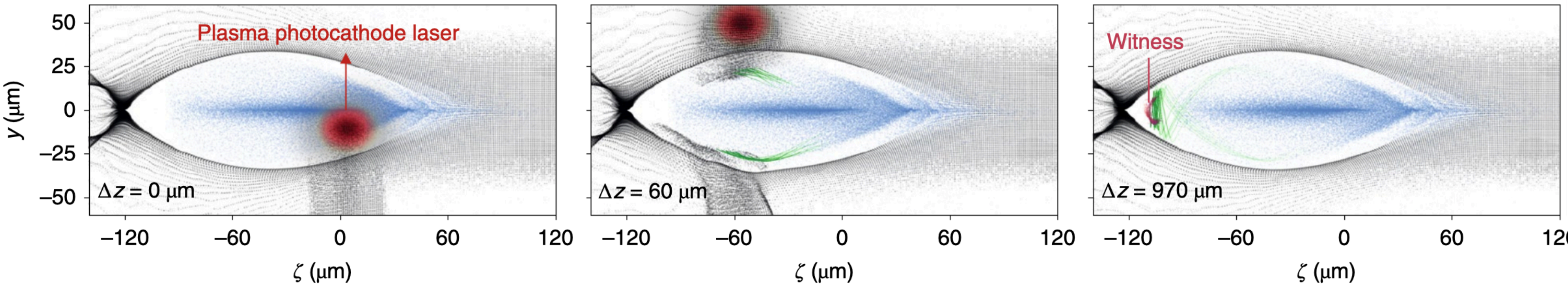
Plasma Photoinjectors

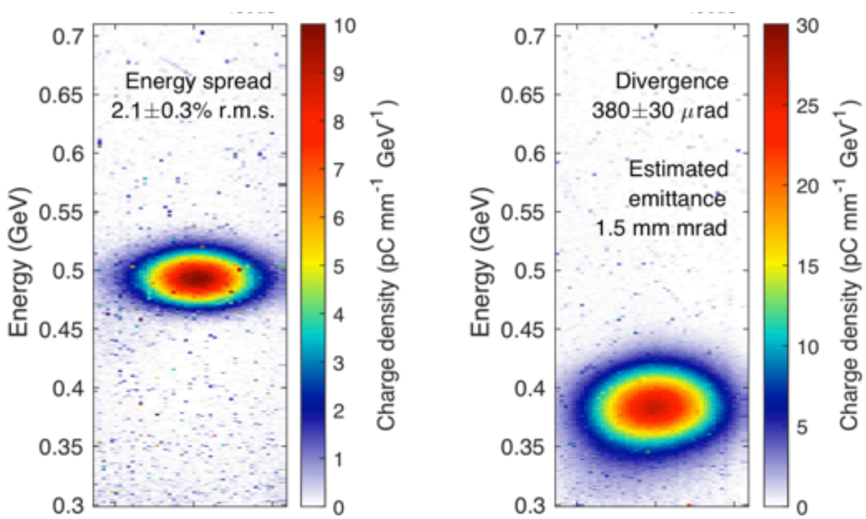
- 100 GeV/m
- fs beams, µm size
- Promise orders of magnitude improvement in emittance
- Injection from: TH, Ionization, DDR, CP…

Development of High-Brightness Electron Sources e.g. Laser Triggered Injection in Electron-beam Driven PWFA

‘Trojan Horse’ Injection

See presentations by: Bernhard Hidding WG1 TR19:00 & Fahim Habib WG1 W17:00





A. Deng et al. *Nature Physics* August 2019

- Team of students and postdocs developed the techniques to align, synchronize injection and characterize the injected beams
- Measured beam parameters inline with expected values from simulations
- Experiments at FACET-II will optimize this technique (co-linear injection)

Success of E-210 has generated a family of follow-up proposals for FACET-II: E-31X: Trojan Horse-II, Plasma Torch, Dragon Tail, Plasma Afterglow, Icarus

Development of High-Brightness Electron Sources e.g. Laser Triggered Injection in Electron-beam Driven PWFA

'Trojan Horse' Injection

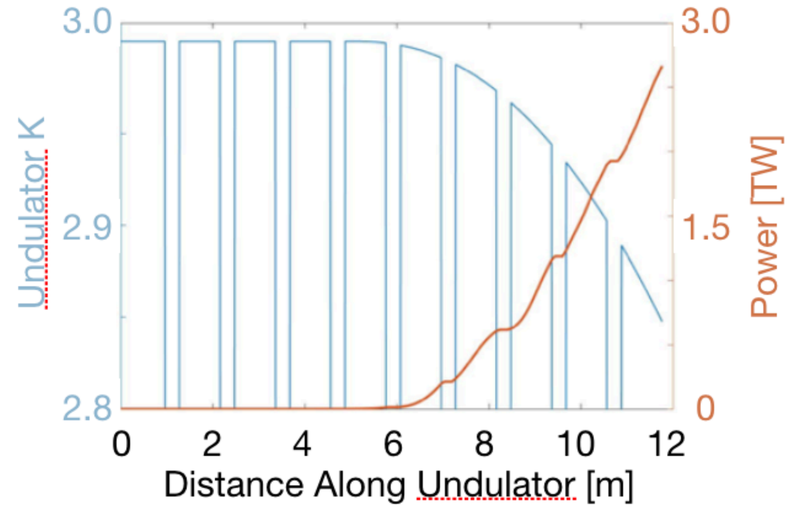
See presentations by: Bernhard Hidding WG1 TR19:00 & Fahim Habib WG1 W17:00

Example FEL Applications:

- TerraWatt Peak Power
- Attosecond Pulses
- Photon Energies > 20keV

HEP Studies:

- Collider level emittance



Results of FACET-II science program are needed to optimize the design of a future demonstration facility

- Path to collider level 10-100nm emittance beams without damping rings

A. Deng et al. *Nature Physics* August 2019

Success of E-210 has generated a family of follow-up proposals for FACET-II: E-31X: Trojan Horse-II, Plasma Torch, Dragon Tail, Plasma Afterglow, Icarus

See presentation by Sebastien Corde WG1-5 Monday 16:20

E-305: Beam Filamentation & Bright Gamma-ray Bursts

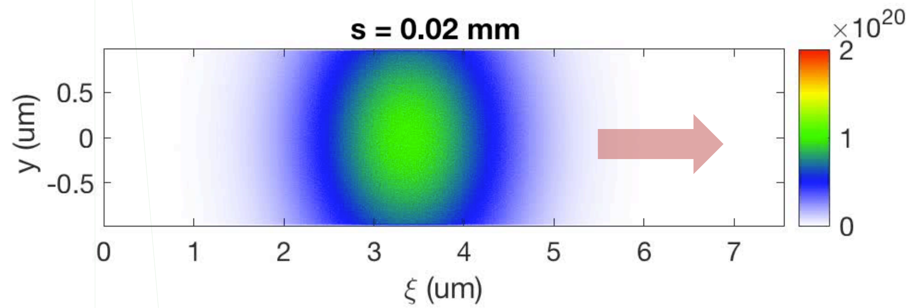
Relativistic streaming instabilities are pervasive in astrophysics

Transverse beam stability:

- If $k_p \sigma_r \leq 1$ the beam is focused towards a stable equilibrium: stable plasma-wave excitation.
- If $k_p \sigma_r > 1$ the beam undergoes transverse instabilities.

E-305 experiment

FACET 10 GeV Electron Bunch
Evolution during propagation over 1.5 mm of Al ($1.8 \cdot 10^{23}$ cm^{-3})



Charge	Normalized emittance	Angular spread	Beam size	Bunch length	Peak current
2 nC	3 mm.mrad	68.74 µrad	2.23 µm	1.5 µm	150 kA

Plasma return current
flows inside the relativistic e^- beam.
Two inter-penetrating e- flows.

Large variety of EM-modes
can develop from noise
Weibel (CFI), Oblique, Two-stream
They break up the beam.

Which mode has the fastest growth rate?
What is the amplitude of those modes?
How do they affect the beam?

FACET-II beam allows exploration of high γ and wide range of n_b/n_p (10^{-4}-1), which is ideal to explore growth and interplay between the two instabilities

See presentation by Sebastien Corde WG1-5 Monday 16:20

E-305: Beam Filamentation & Bright Gamma-ray Bursts

INSTITUT POLYTECHNIQUE DE PARIS | UCLA | SLAC

Relativistic streaming instabilities are pervasive in astrophysics

Transverse beam stability:

- If $k_p\sigma_r \leq 1$ the beam is focused towards a stable equilibrium: stable plasma-wave excitation.
- If $k_p\sigma_r > 1$ the beam undergoes transverse instabilities.

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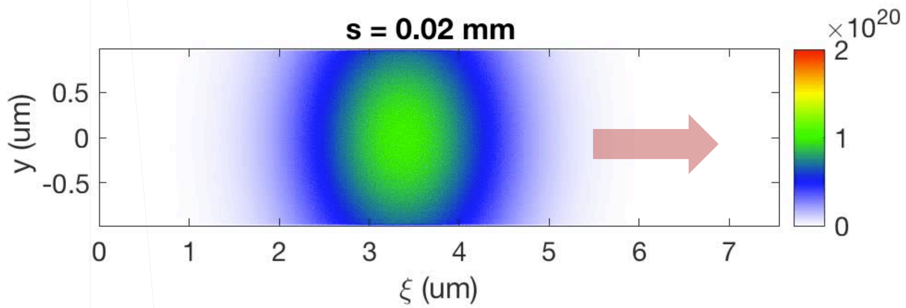

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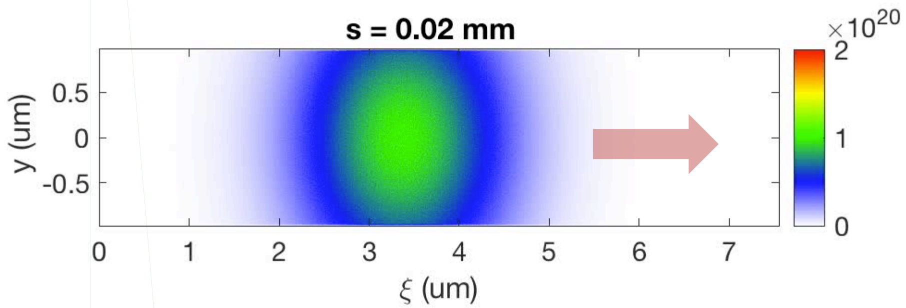

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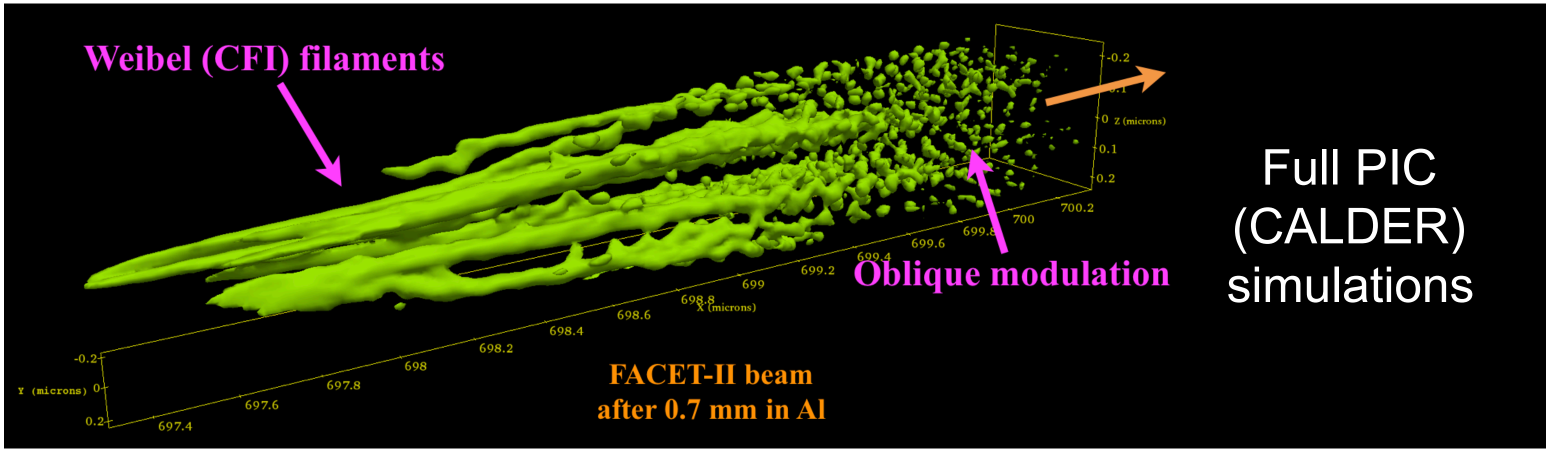
E-305: Beam Filamentation Instabilities and ɣ-ray Generation

Gamma rays in solids

Once filamentation instability has developed, beam electrons experience large electromagnetic fields, bending their trajectories, and leading to synchrotron-type gamma-ray emission.



Potential for giant gamma-ray bursts:

- Study of gamma-ray yield as a function of plasma density and n_b/n_p
- Wakefield versus filamentation regime
- Could exceed 10% conversion efficiency from electrons to gamma rays, with unique opportunities for gamma-ray source applications and for 2-step positron sources

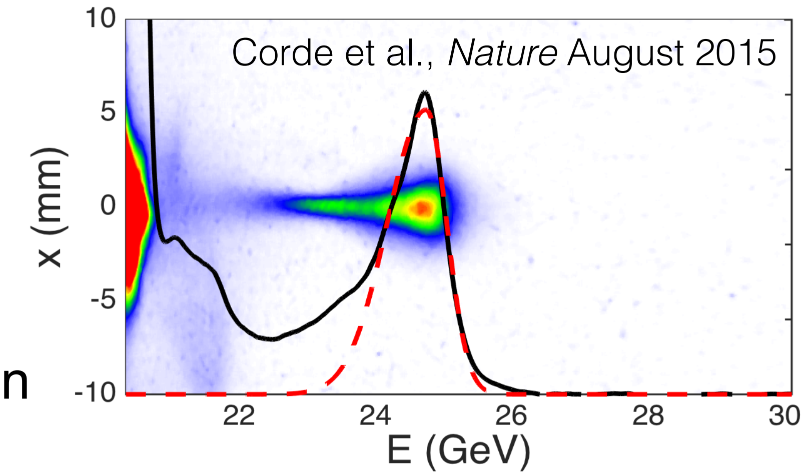
Collaboration combines interests of several groups in astrophysical plasma instabilities, plasma focusing, novel positron production experiments

FACET/FACET-II Have a Unique Role in Addressing Plasma Acceleration of Positrons for Linear Collider Applications

See plenary by Carl Lindstrøm W09:00

Multi-GeV Acceleration in **Non-linear wakes**

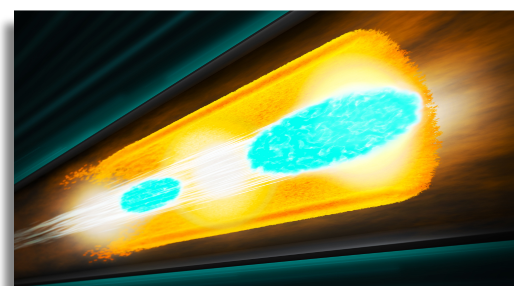
- New self-loaded regime of PWFA
- Energy gain 4 GeV in 1.3 meters
- Low divergence, no halo

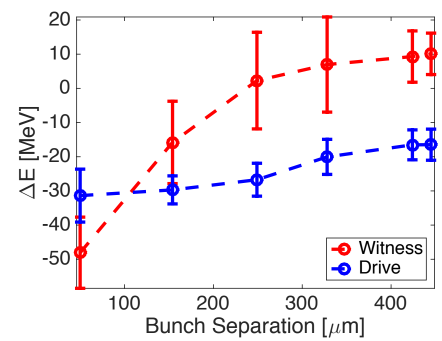


Hollow Channel Plasma Wakefield Acceleration

- Engineer Plasma to Control the Fields
- No focusing on axis
- Measured transverse and longitudinal wakefields

Gessner et al., *Nature* Communications 2016
Lindstrom et al., *Phys. Rev. Lett.* 2018

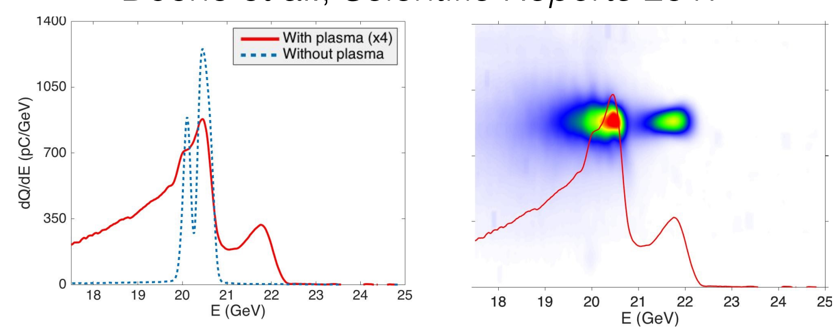




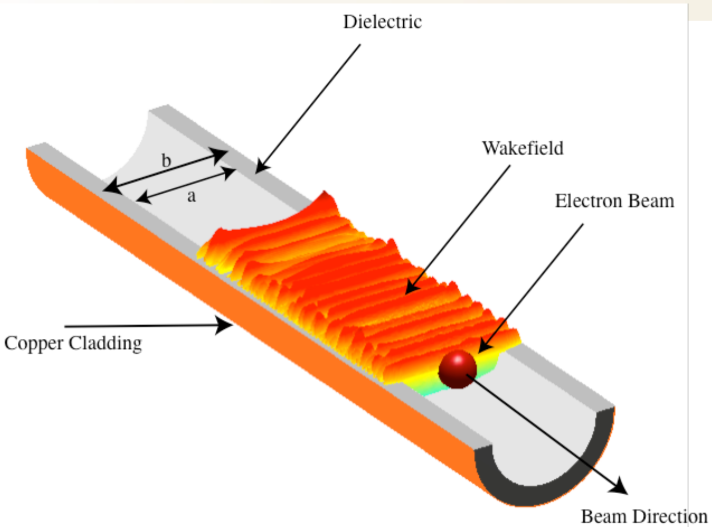
Quasi-linear Wakefield Acceleration

- > 1 GeV energy gain in 1.3 meters
- Of interest to both the PWFA and LWFA for linear collider applications
- This technique can be used to accelerate a positron witness beam in electron wake

Doche et al., *Scientific Reports* 2017

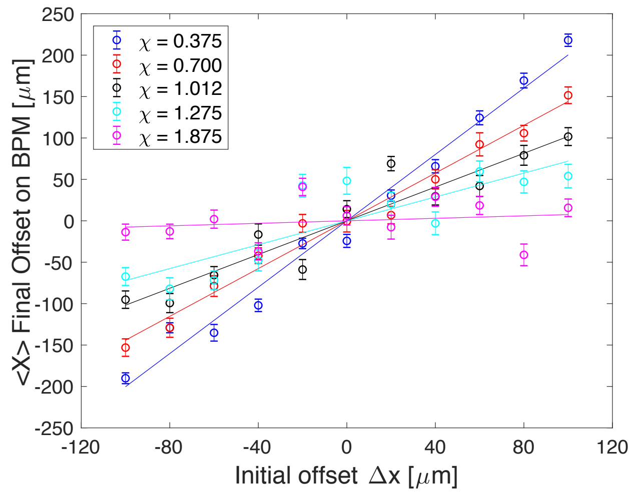


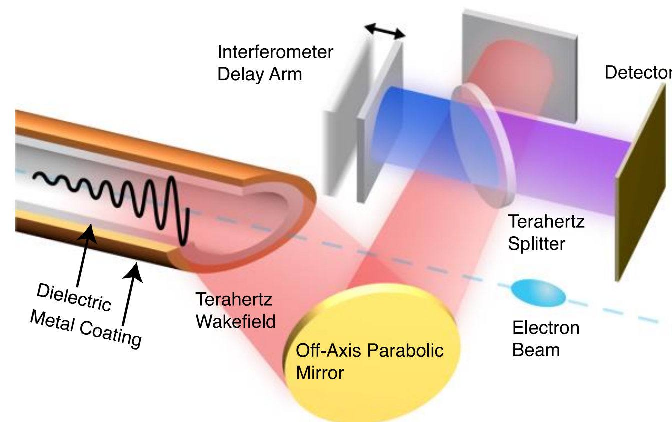
FACET/FACET-II Extreme Beams Enable Record Performance for Dielectric Wakefield Acceleration



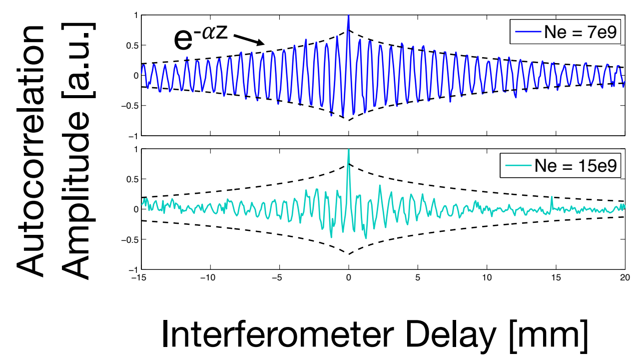
Quartz tubes
3-15cm long
300μm diameter

Suppression of Transverse Wakefields with Elliptical Beams in Slab Structures





High Field Damping
Above 850MeV/m



Measured Acceleration:

Single Bunch (300/400) 15 cm	**1.3 GV/m**
Two Bunch (300/400) 10 cm	**320 MV/m**

B.D. O'Shea et al. *Nature Communications*, 7, 12763 (2016)

B.D. O'Shea et al. *in preparation*

B.D. O'Shea et al. *Physical Review Letters*, Accepted September 2019

E-321 at FACET-II will build towards meter scale GeV/m acceleration using novel structure geometries and materials

E-320: Probing Strong-field QED at FACET-II
Collision of ~10^{20} W/cm² laser pulses with 10-13 GeV electrons

See presentations at ExHILP2019: https://web.stanford.edu/group/pulse_institute/exhilp/

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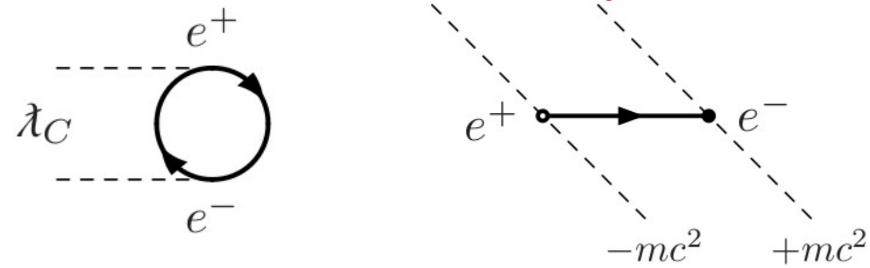
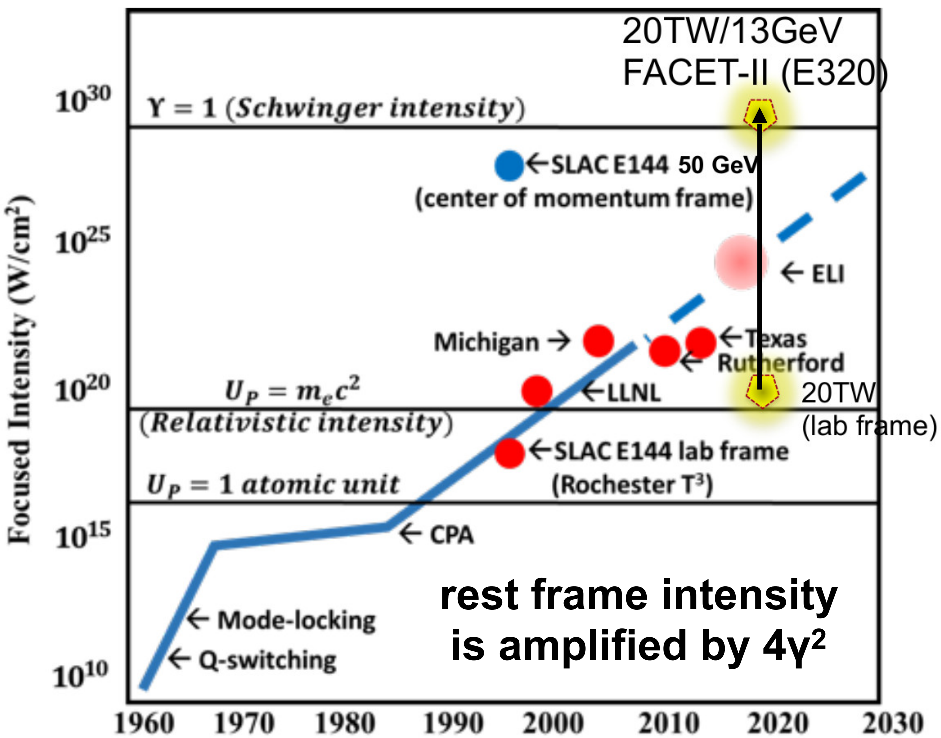
QED critical field: $E_{cr} = mc^2/e\lambda\!\!\!^{-}_C \sim 10^{18}$ V/m

Energy: mc^2 ~ MeV; **Length**: $\lambda\!\!\!^{-}_C = \hbar/mc \sim 10^{-13}$ m;

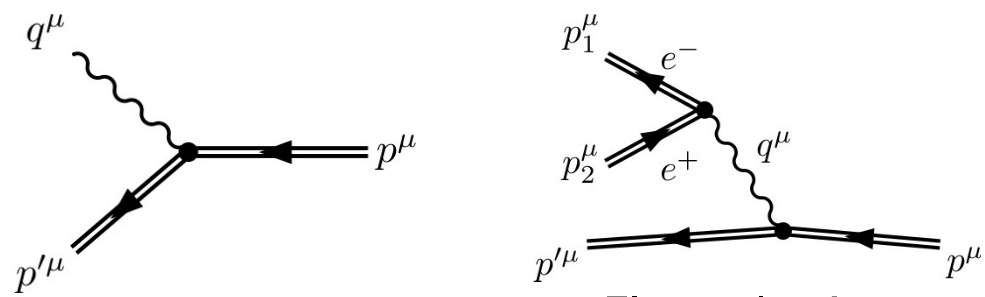
Vacuum fluctuations: uncertainty principle limits extent to $\lambda\!\!\!^{-}_C$, critical field can transfer mc^2: real pair



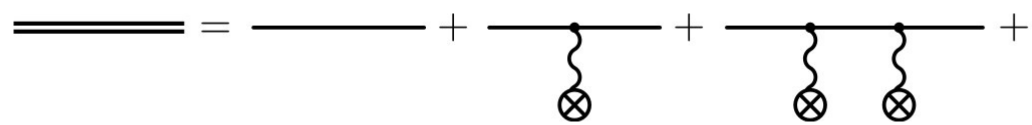


Critical intensity: ~10^{29}W/cm², can be achieved in the rest frame of ultrarelativistic electrons: $\chi=\Upsilon\sim\gamma E/E_{cr}$ (γ: Lorentz factor; E: electric field)

Fundamental Strong-field QED processes



Photon emission **Electron/positron pair production**



Dressed states ($a_0 \gtrsim 1$): laser nonperturbative: concerted interaction with multiple laser photons

Quantum regime ($\chi=\Upsilon\gtrsim 1$): stochastic photon emission & recoil disruption of trajectories; pair production no longer exponentially small

E-320: Probing Strong-field QED at FACET-II
Collision of ~10^{20} W/cm^2 laser pulses with 10-13 GeV electrons

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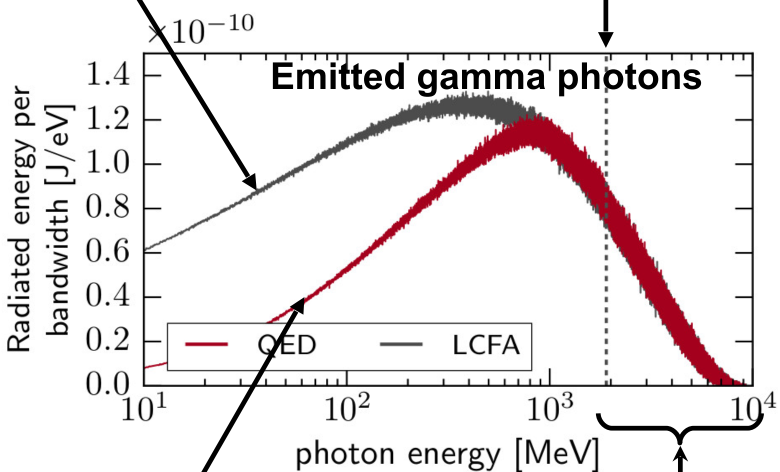
Aim: measuring emitted gamma photons + scattered electrons and produced positrons

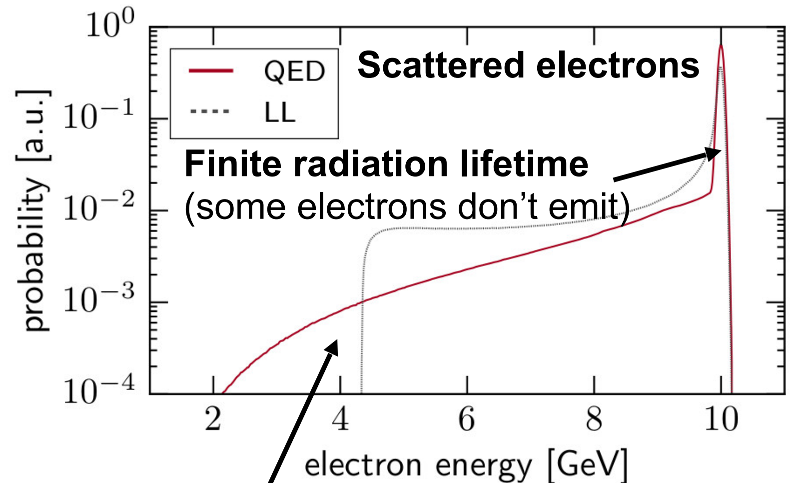
Standard numerical code: local constant field approximation

single-photon Compton scattering edge

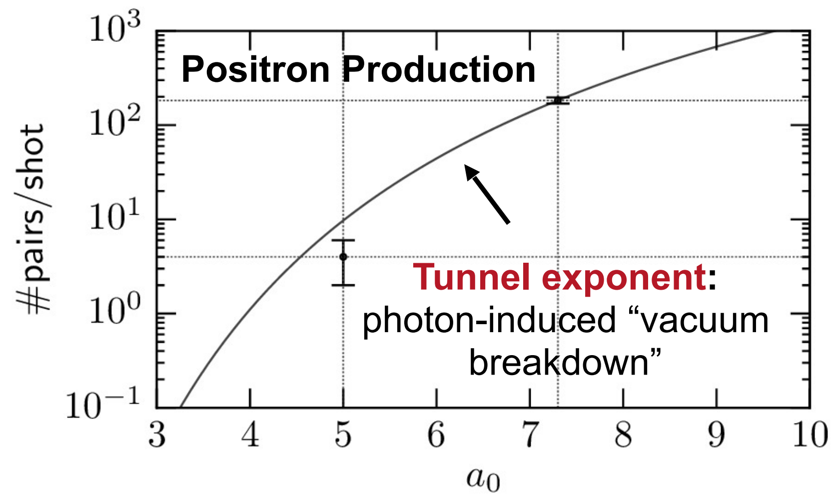


LCFA breakdown: formation length comparable with laser wavelength

"**high harmonics**": requires absorption of multiple laser photons



Radiation reaction (emission of multiple photons)
Classical (Landau/Lifshitz): sharp edge (cooling)
Quantum (QED): stochasticity (diffusive behavior)



Timeline: Spring 2020: backgrounds (positrons) & first measurements (electrons), Summer/Fall 2020: pair production. Future: laser upgrade, gamma spectrum, etc.

Collaboration: Carleton (Canada); Aarhus (Denmark); École Polytechnique (France); MPIK & HI Jena (Germany); Lisboa (Portugal); Imperial & Belfast (UK); Cal Poly & Colorado & LLNL & Nebraska & SLAC & UCLA (USA)

Simulations: M. Tamburini (Heidelberg) & M. Vranic (Lisbon)

FACET-II Annual Science Workshops
December 2012, October 2015, 2016, 2017…2019

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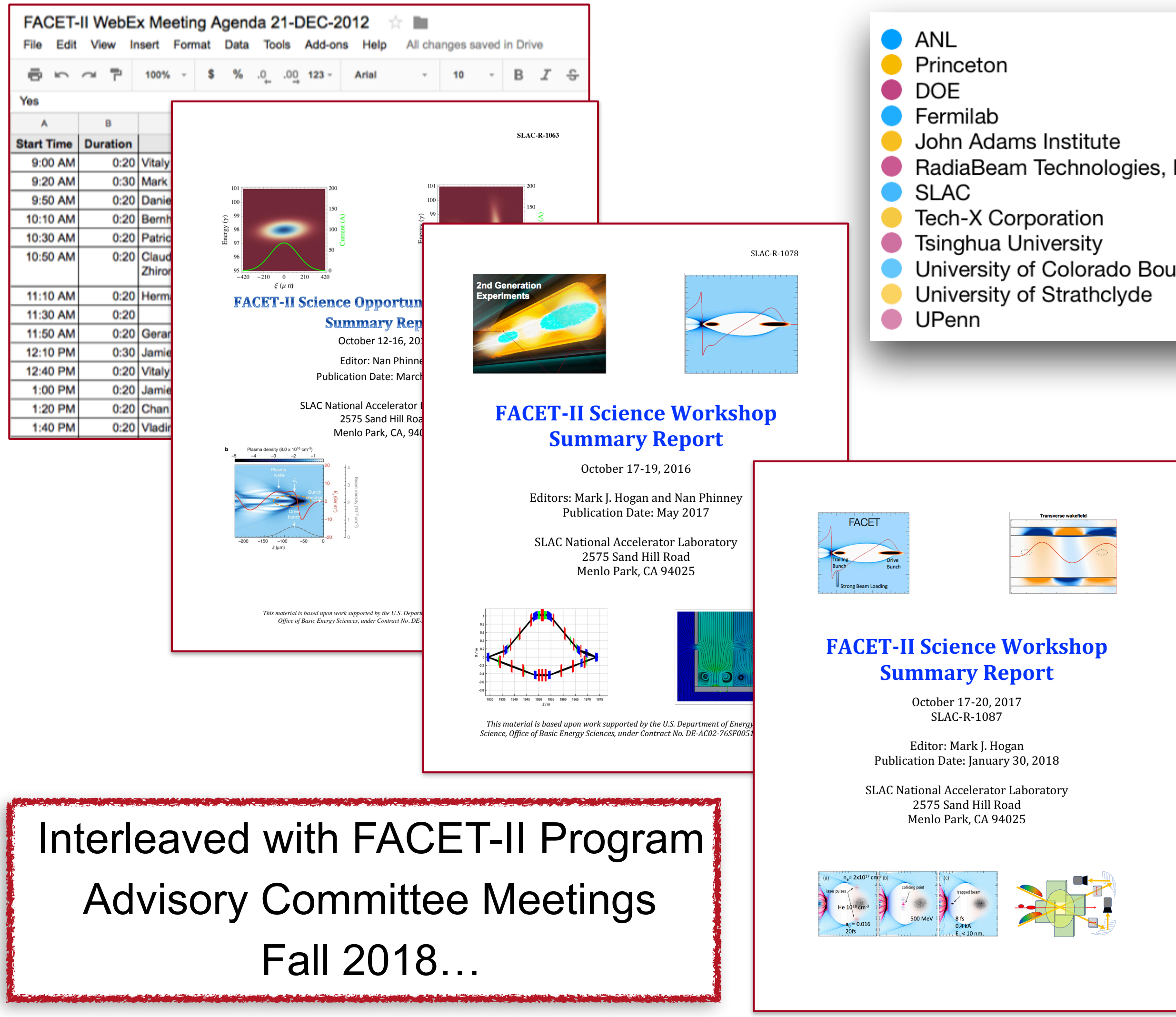

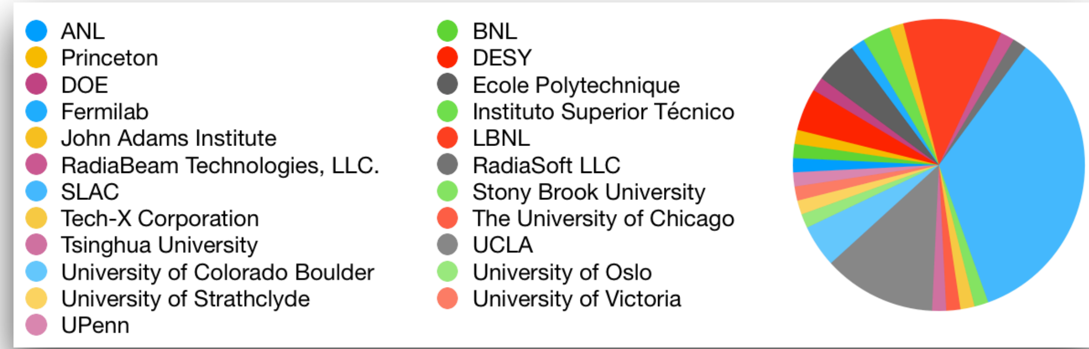

Interleaved with FACET-II Program Advisory Committee Meetings Fall 2018…

Next Science Workshop October 2019 to discuss:

- Facility status
- Technical readiness of first experiments
- Science case for positrons & new ideas
- FEL applications

More information and registration:
https://conf.slac.stanford.edu/facet-2-2019/