Ultimate Beams at FACET-II

Workshop on Beam Acceleration in Crystals and Nanostructures

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U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

FACET project history

Primary Goal:

- Demonstrate a single-stage high-energy plasma accelerator for electrons

Timeline:

- CD-0 2008
- CD-4 2012, Commissioning (2011)
- Experimental program (2012-2016)

A National User Facility:

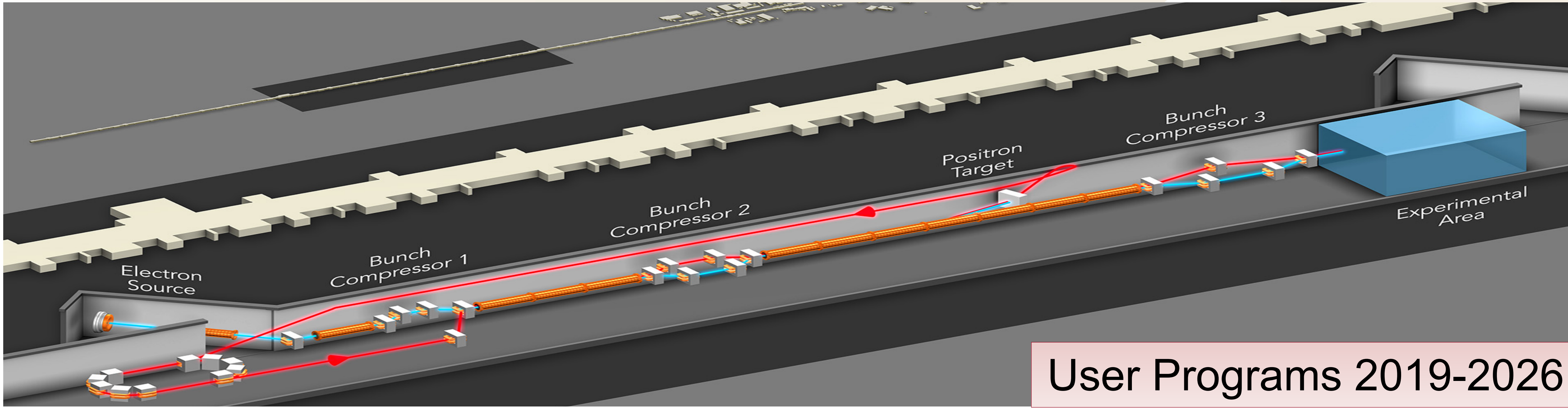
- Externally reviewed experimental program
- 150 Users, 25 experiments, 8 months/year operation

Key PWFA Milestones:

✓ Mono-energetic e- acceleration
✓ High efficiency e^- acceleration, ***Nature*** *2014*
✓ First high-gradient e^+ PWFA , ***Nature*** *2015*
✓ High brightness beams from plasma, ***Nature Physics*** *2019*

The premier R&D facility for PWFA: Only facility capable of e+ acceleration, Highest energy beams uniquely enable gradient > 1 GV/m

FACET-II project



User Programs 2019-2026

Timeline:

- Nov. 2013, FACET-II proposal, Comparative review
- CD-0 Aug. 2015
- CD-1 Oct. 2015
- CD-2/3A Sep. 2016
- CD-2/3 Apr. 2018
- CD-4 2021
- Experimental program (2019-2026)

Key R&D Goals:

- High brightness beam generation, preservation, characterization
- e^+ acceleration in e^- driven wakes
- Staging challenges with witness injector
- Generation of high flux gamma radiation

Three stages:

- Photoinjector (e- beam only)
- e+ damping ring (e+ or e- beams)
- "sailboat" chicane (e+ and e- beams)

On schedule to start commissioning in 2019

FACET-II Annual Science Workshops
Dec. 2012, Oct. 2015, Oct. 2016 and Oct. 2017, <u>*Oct.28-Nov.1 2019*</u>

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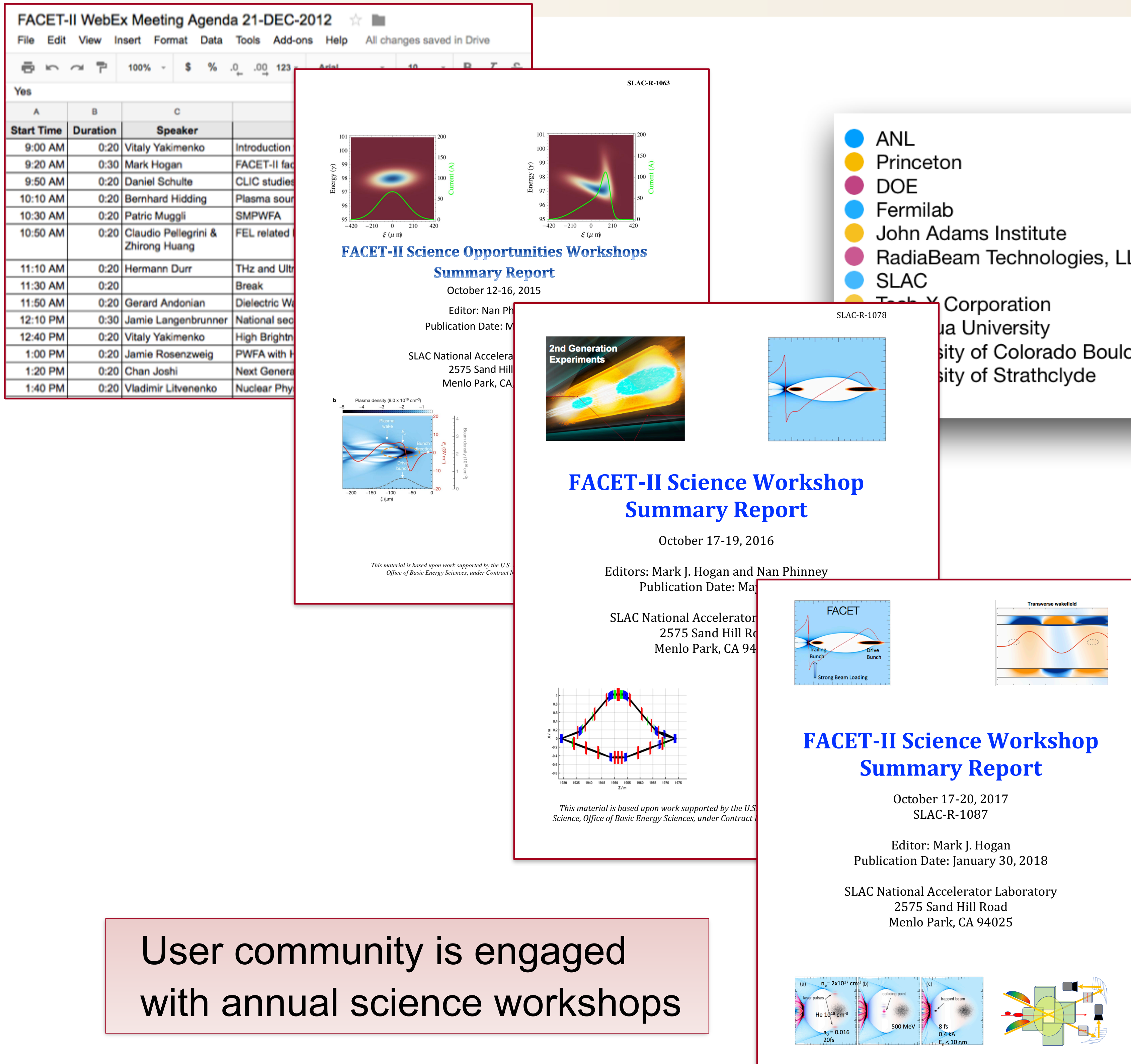

2017 Workshop:
64 Participants
23 Institutions

User community is engaged with annual science workshops

Excellent alignment with Roadmap priorities

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

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35 proposals (for Stage 1 only) were reviewed at a recent PAC:

- 7 received “Excellent” ranking
- 23 were ranked "Very Good" or “Good"
- 2 proposals were ranked “Fair”
- 3 were not ranked and are encouraged to resubmit

Proposals with “Excellent” ranking:

- Energy Doubling of Narrow Energy Spread Witness Bunch while Preserving Emittance with a High Pump-to-Witness Energy Transfer Efficiency
- Transverse wakefields and instabilities in PWFA
- Generation and Acceleration of Positrons at FACET II
- Optical visualization of beam-driven PWFA
- Trojan Horse-II
- **Beam filamentation and bright Gamma ray Burst**
- **Probing Strong-field QED at FACET-II**

Proposals represent:

Fermilab, DESY, Max-Planck-Gesellschaft, Universidade Técnica de Lisboa, Universitas Osloensis, The University of Chicago, The University of Texas at Austin, CERN, Universität Hamburg, SLAC National Accelerator Laboratory, Stanford, CU, Los Alamos National Laboratory, PPPL Princeton Plasma Physics Laboratory, UCLA, University of Oxford, Stony Brook University, Penn University of Pennsylvania, Cal Poly San Luis Obispo, University of Strathclyde Glasgow, Université Paris Sud

Active Engagement Between Facility & User Community – Illustrated by Design and QuickPIC Simulation of 'First Experiment'

Key Upgrades:

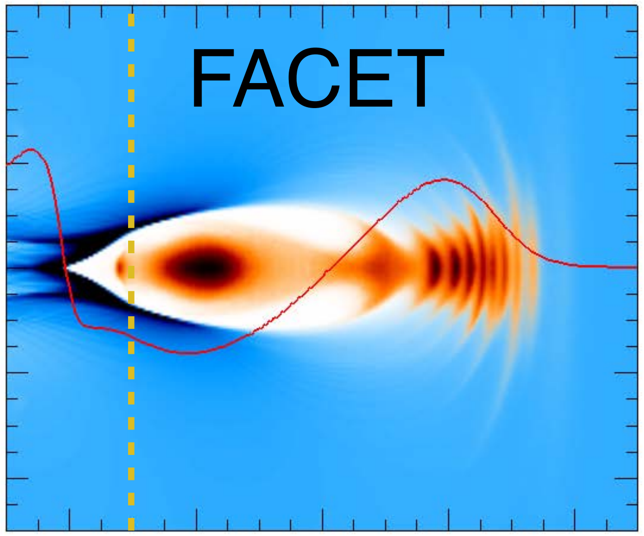
- Photoinjector beam
- Plasma source with matching ramps
- Differential pumping
- Single shot emittance diagnostic

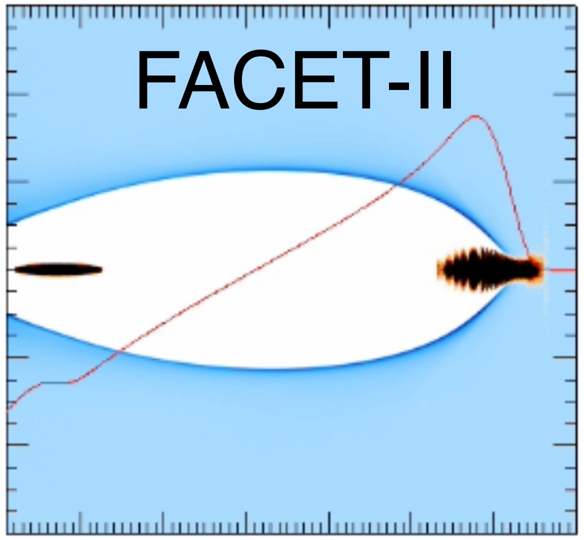
Science deliverables:

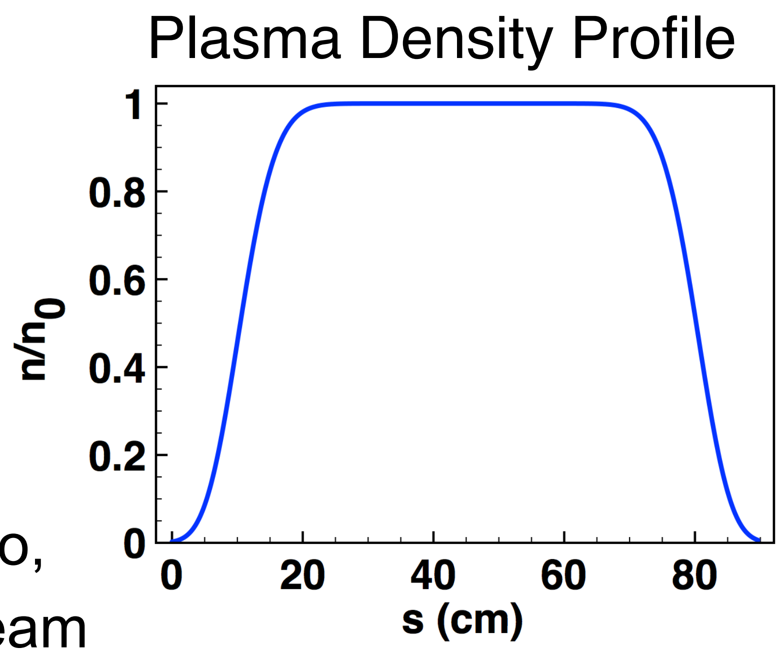
- Pump depletion of drive beam with high efficiency & low energy spread acceleration
- Beam matching and emittance preservation

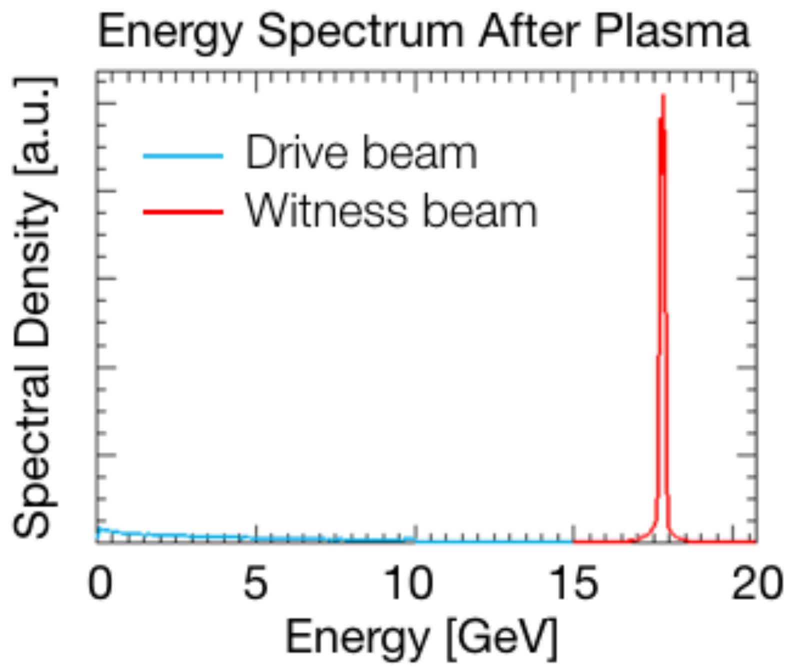
Simulated Performance:

- SLAC & UCLA groups iterated for optimal bunch separation, charge ratio, peak currents, plasma density and beam waist conditions









PAC 'Excellent' rankings re-iterated that roadmap priorities are well developed in proposed experimental program

Community Coming Together Around Ideas for Testing Mechanisms That May Limit Beam Quality

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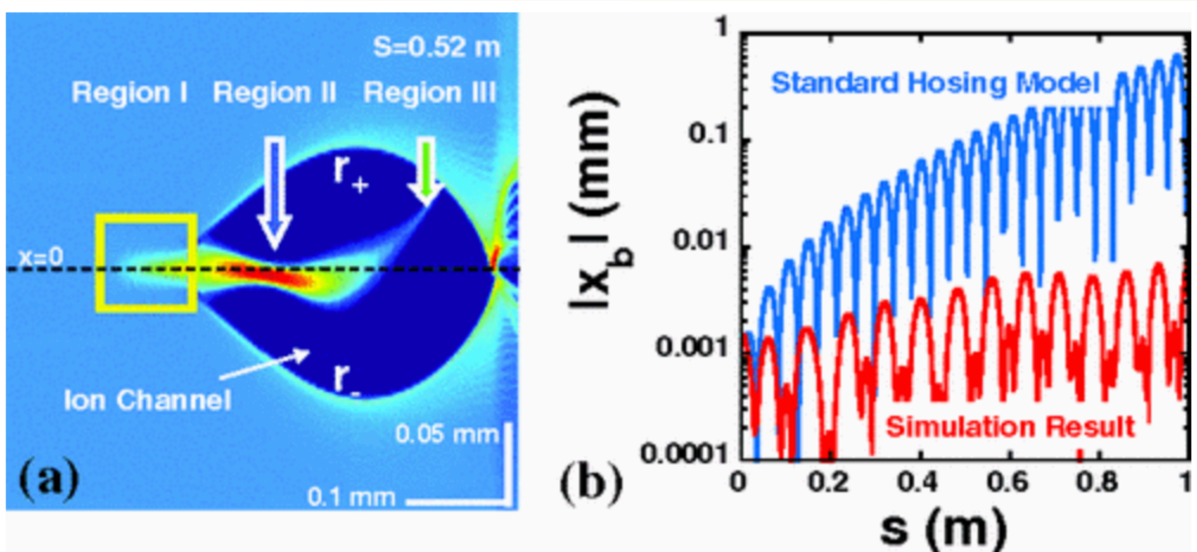
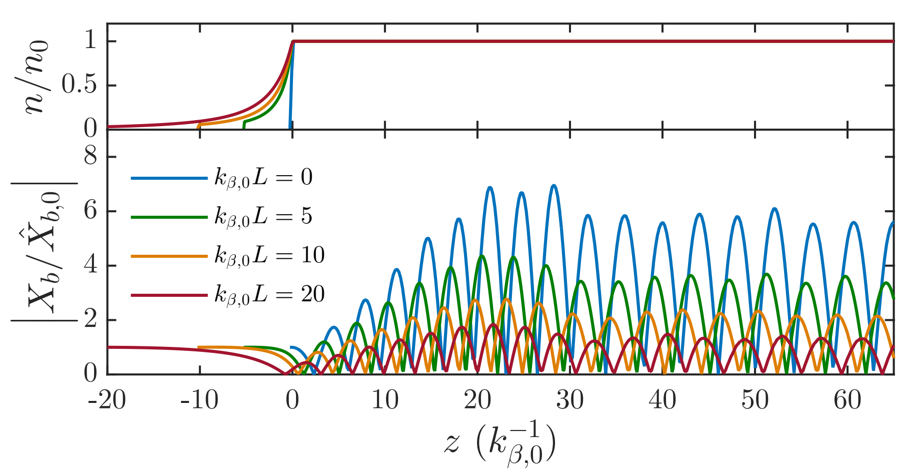


Many **mechanisms of emittance growth** have been put forward, e.g. ion motion, hosing…

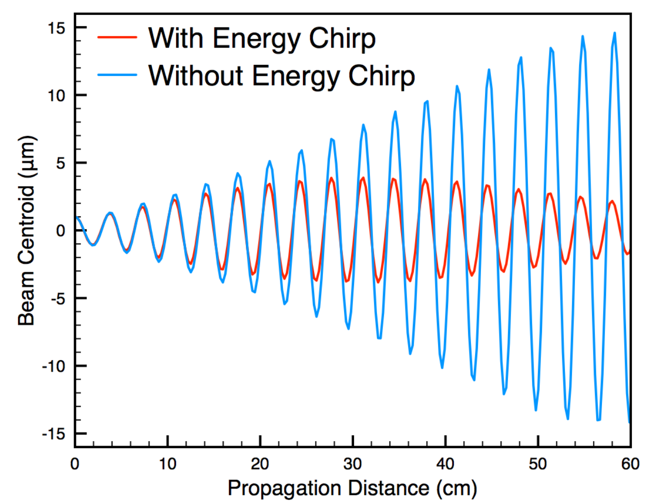
D. Whittum et al. PRL 67, 991 (1991) **LBNL/SLAC**
J. Rosenzweig et al., 95, 195002 (2005) **UCLA**
C. Huang et al., PRL 99, 255001 (2007) **UCLA**
V. Lebedev et al., PRST-AB 20, 121301 (2017) **FNAL**

Plamsa ramps

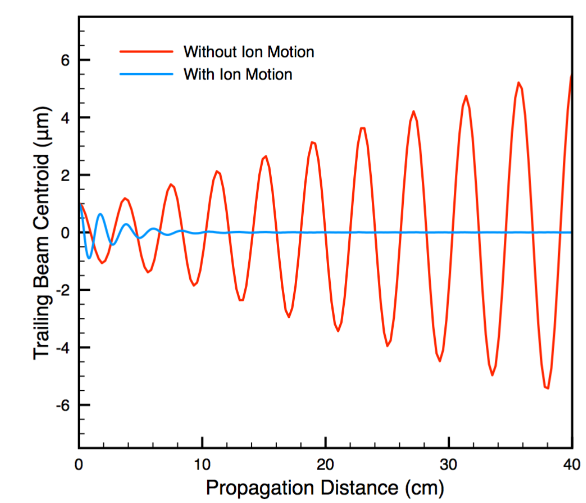


T. Mehrling et. al., PRL 118, 174801 (2017) **DESY/LBNL**

Energy Spread



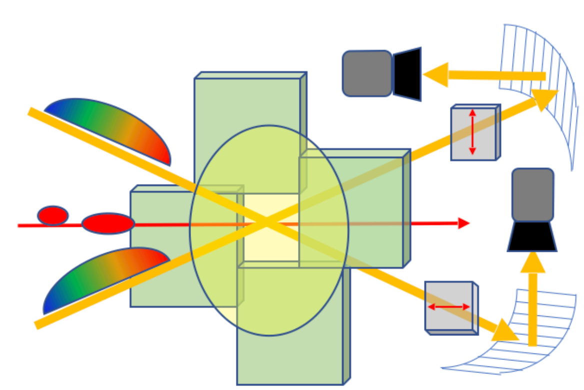
Ion Motion



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

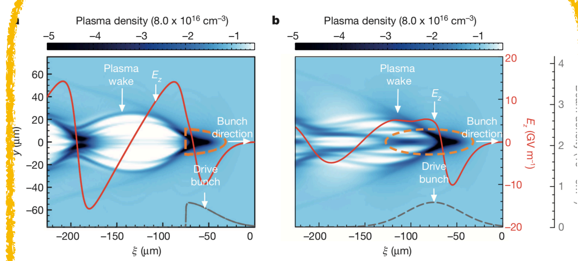


Goal is to measure correlation along ~1ps long bunch

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

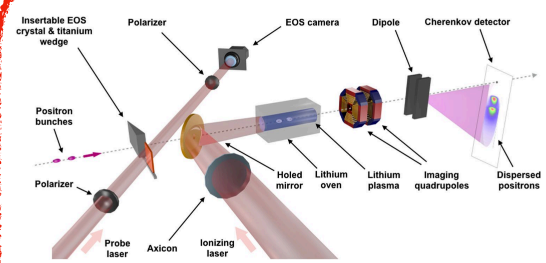
High-Quality Positron Beams Will Be a Unique Feature of FACET-II – but not available until 2022

FACET positron acceleration experiments examples



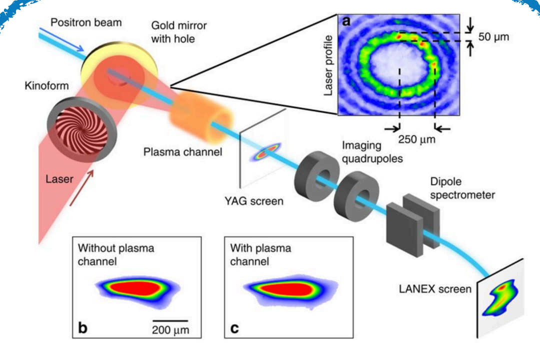
Single positron bunch acceleration
Energy gain of 5 GeV

S. Corde et al., Nature 524, 442 (2015)



- Two positron bunches
- Energy gain of 1.7 GeV

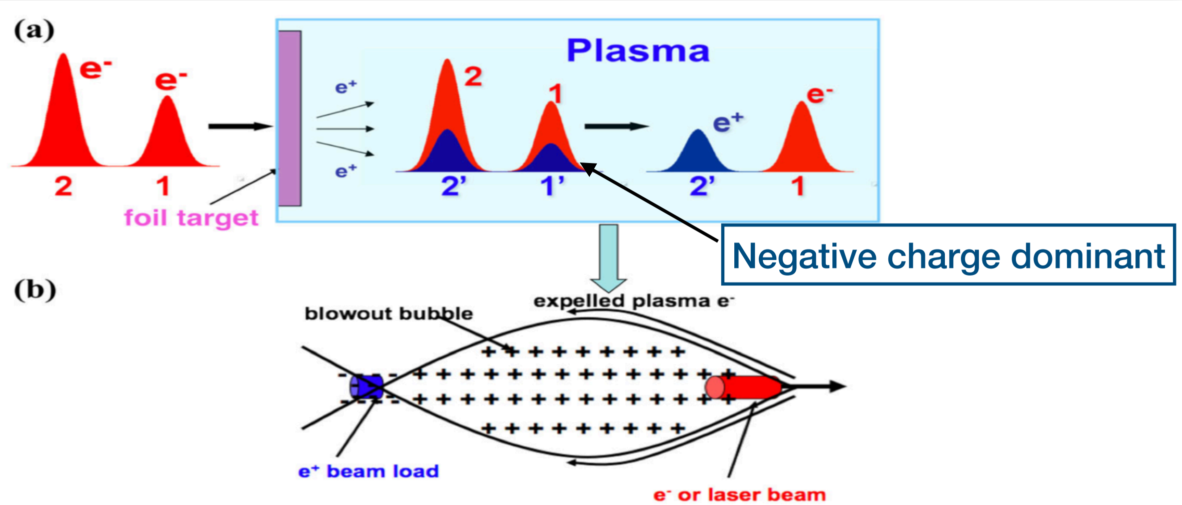
A. Doche et al., Scientific Reports (2017)



- Laser induced hollow channel plasma investigated
- Quantified Trans. & Long. Wakefields

S. Gessner, et al.
Nature Communications 7, 11785 (2016)

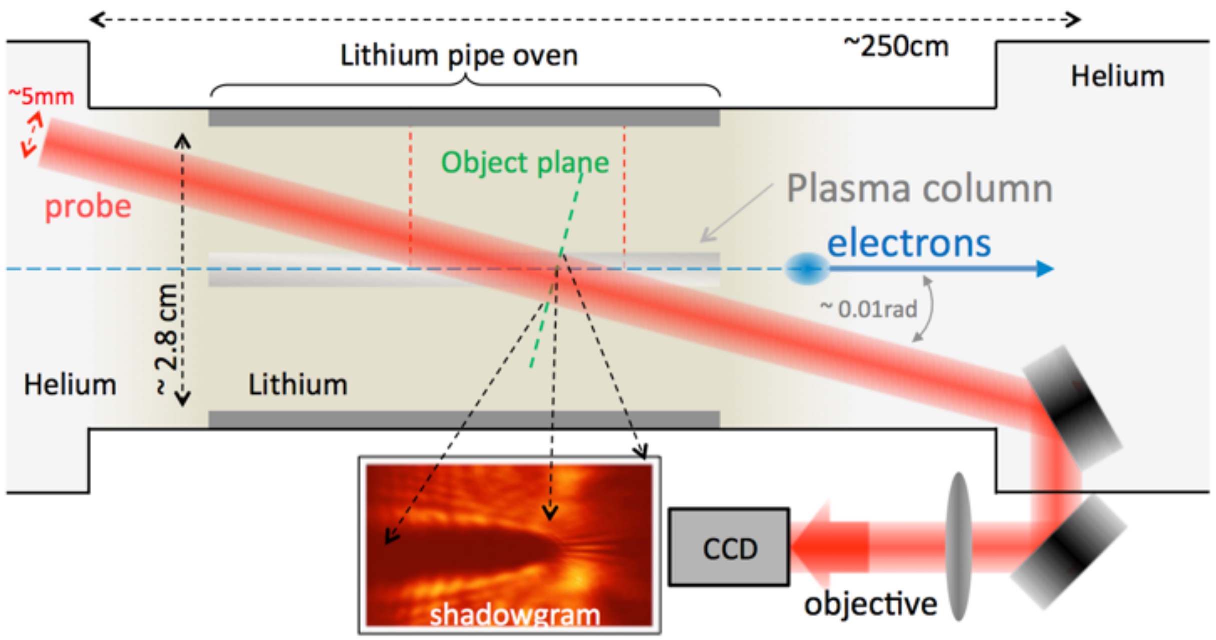
Several candidate regimes for positron acceleration in plasmas but much of the physics remains unstudied experimentally

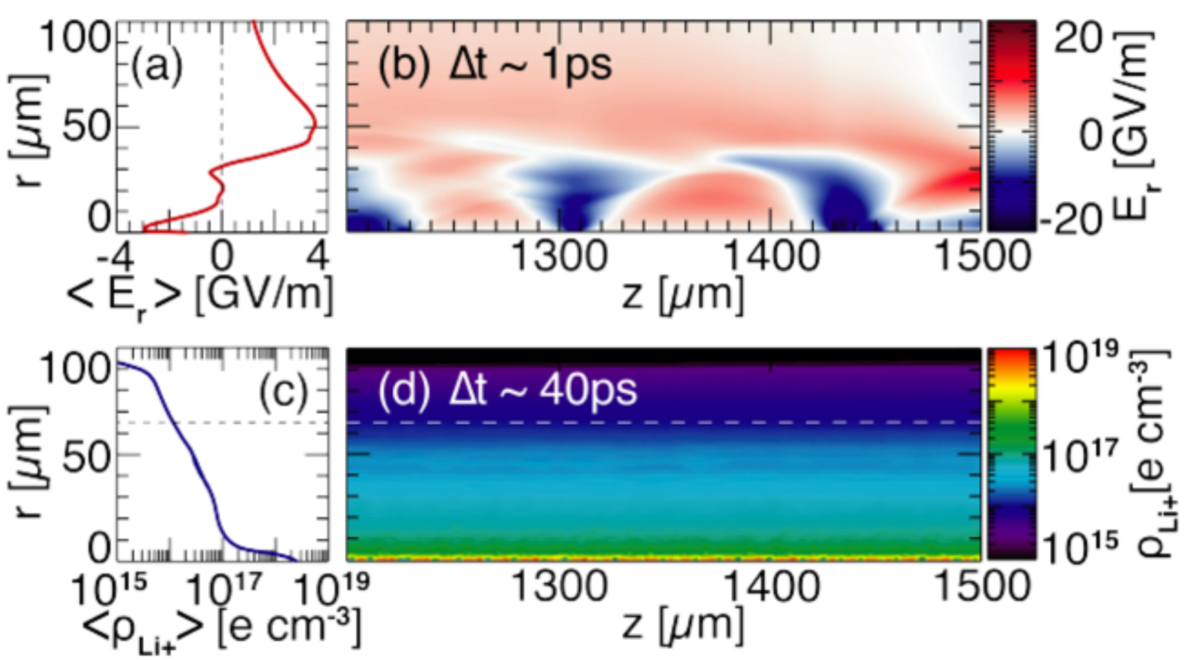


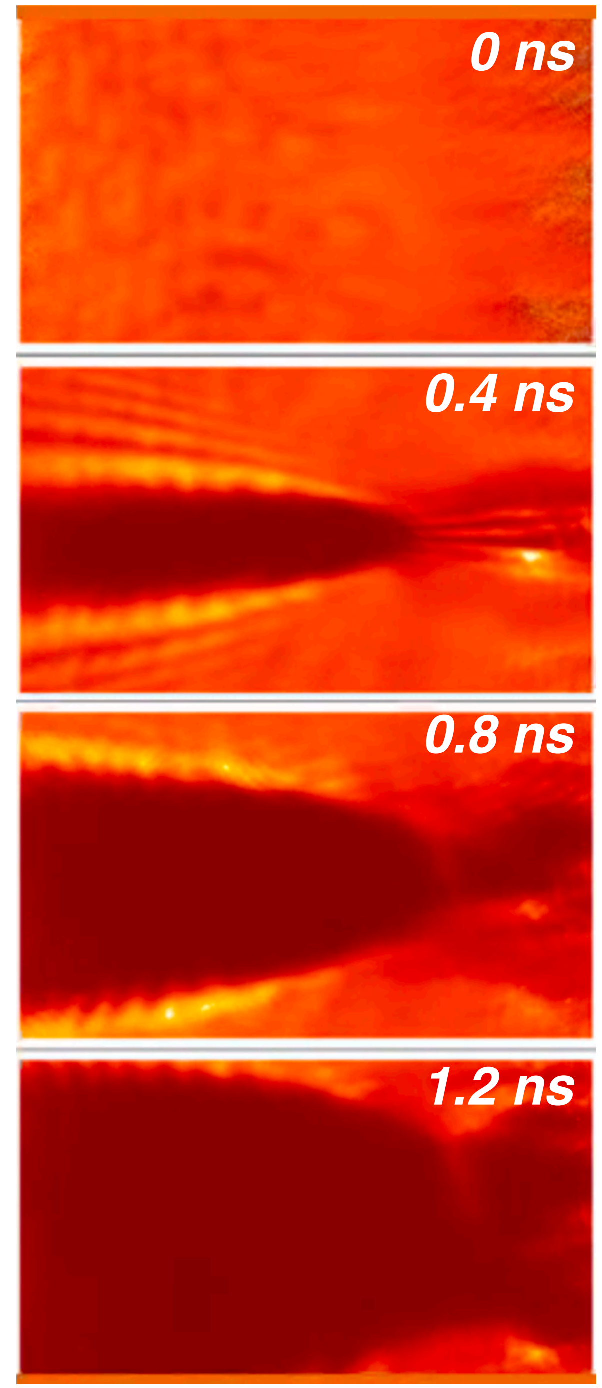
X. Wang, et. al., Positron Injection and Acceleration on the Wake Driven by an Electron Beam in a Foil-and-Gas Plasma, Phys. Rev. Lett. **101**, 124801 (2008)

One 'Excellent' proposal will be technically challenging to realize but will allow jump starting the positron acceleration program

Beam Driven Non-linear Wakefields Drive Radial Expansion







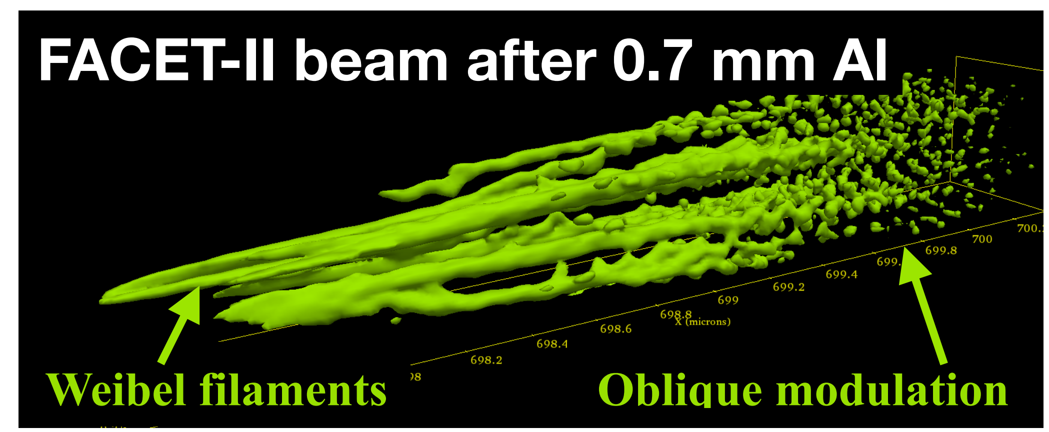
- Non-linear wakes are non-symmetric
- Leads to non-zero average radial electric field
- Radial fields drive ion wakes and plasma expansion
- Perturbations last > 10μs

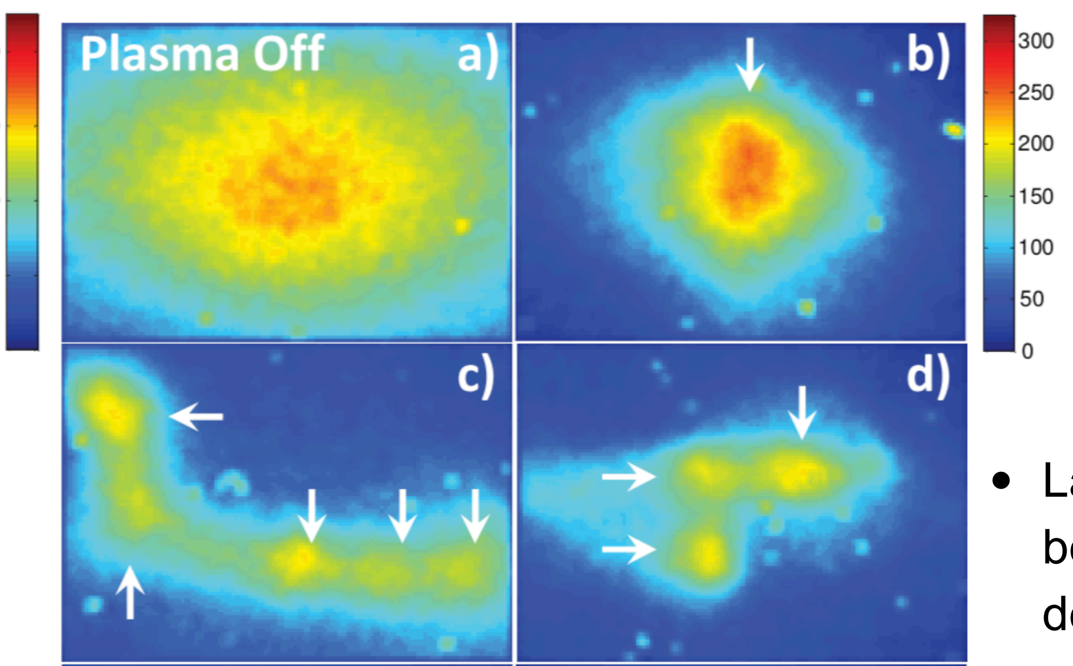
Unexpected results from analysis of FACET data – *to be published* soon

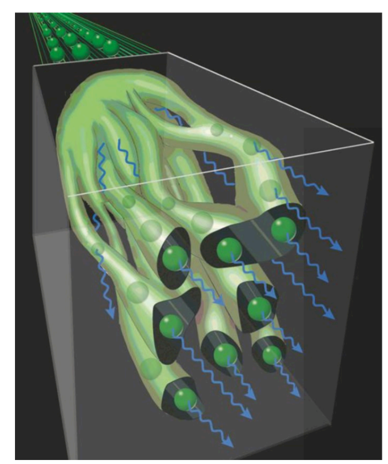
FACET-II experiment on current filamentation instability and Gamma-ray source

Gamma-ray source of unprecedented efficiency and brightness based on synchrotron radiation from beam electrons in extreme magnetic fields of its filaments developed due to the instability

- When electron beam propagates through a plasma, return currents by the plasma electrons are established
- The counter-streaming beam and plasma electrons result in instability and form self-generated beam filaments and electromagnetic fields
- Trajectories of the beam electrons are bent in these fields and synchrotron radiation is emitted
- Predicted in theory scaling of transverse filament size was observed over a wide range of plasma densities in experiments at BNL's ATF with 60 MeV beam ***[Phys. Rev. Lett. 109, 185007 (2012)]*.**



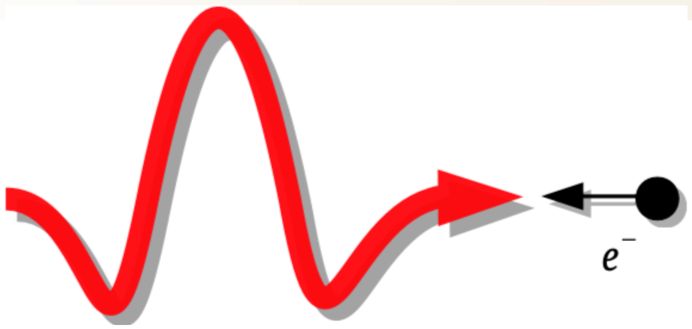




- Large amount of electron beam energy, potentially exceeding 10%, can be converted into gamma-rays for high-energy electron beams and high density plasma, ***[Nature Photon. 12, 319 (2018)]*.**
- Instabilities develop only for extreme beam parameters at high energy

Ability to test this regime was one of the motivations for beam parameters that will be available at FACET II, making the facility well suited to conduct experimental research on relativistic electromagnetic plasma instabilities and gamma-ray source of unprecedented efficiency and brightness.

Strong-Field QED in Laboratory Experiments



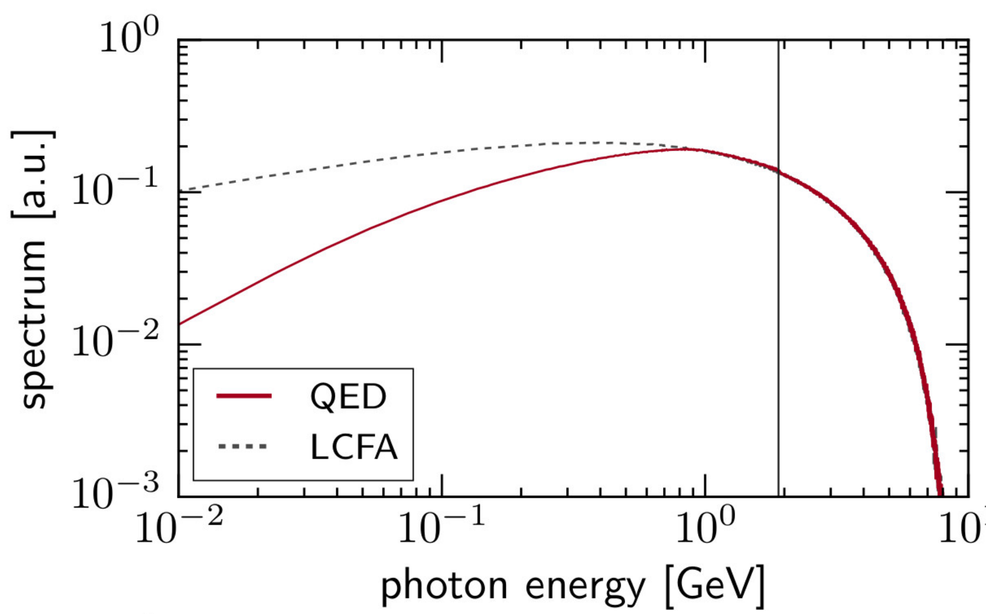
Basic concept:

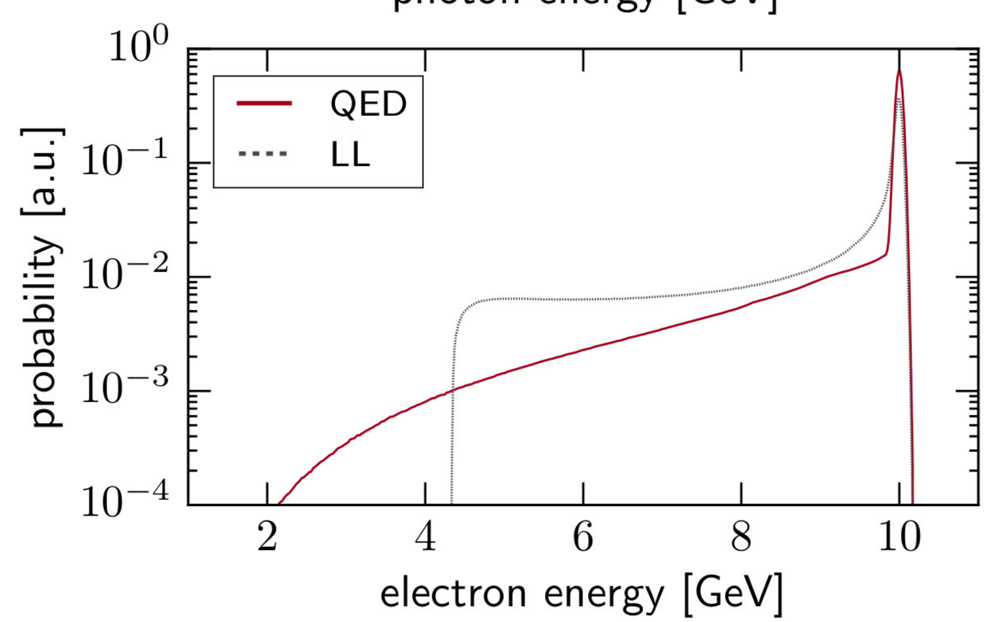
Reaching the QED critical field $E_{cr}=m^2c^3/(e\hbar)$ ~ 10^{18} V/m:

20TW @ 2.5μm implies ~10^{29} W/cm^2 (rest frame intensity)

Major objectives:

- First observation of pair production via vacuum breakdown in locally constant field
- Highly nonperturbative Compton scattering: up to 8 GeV (Compton edge: ≈ 2 GeV)
- Local-constant field approximation (LCFA) breakdown (used in numerical codes)
- Quantum radiation reaction: stochasticity, breakdown of Landau-Lifshitz (LL) model





SF QED experiments at FACET-II will test new physics and will provide critical measurements for code developers

PWFA Research Priorities at FACET-II
Stage 1 Funded. Stage 2 & 3 will Fully Exploit the Potential of FACET-II

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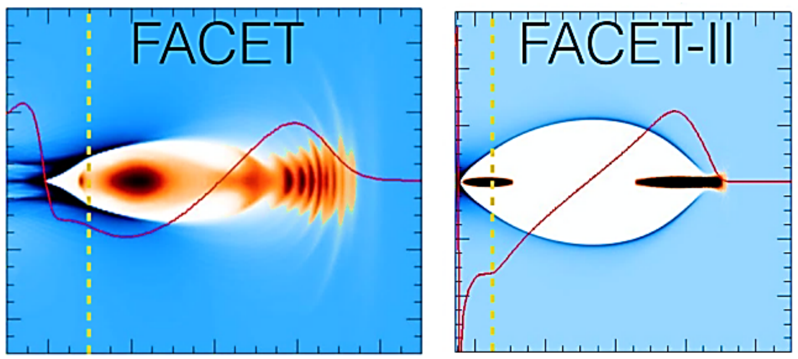
Emittance Preservation with Efficient Acceleration
FY19-21

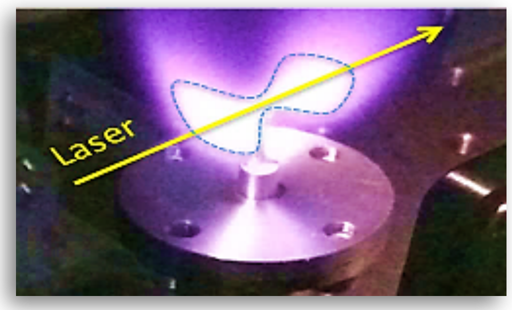
- High-gradient high-efficiency (instantaneous) acceleration has been demonstrated @ FACET
- Full pump-depletion and Emittance preservation at μm level planned as first experiment

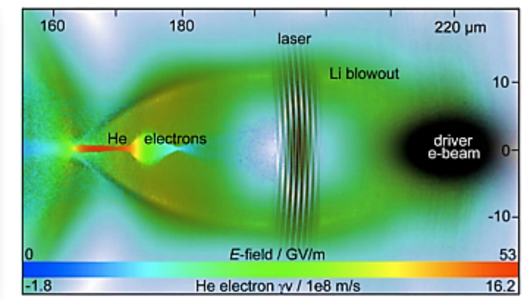


Stage 1

High Brightness Beam Generation & Characterization
FY20-22

- 10's nm emittance preservation is necessary for collider apps
- Ultra-high brightness plasma injectors may lead to first apps



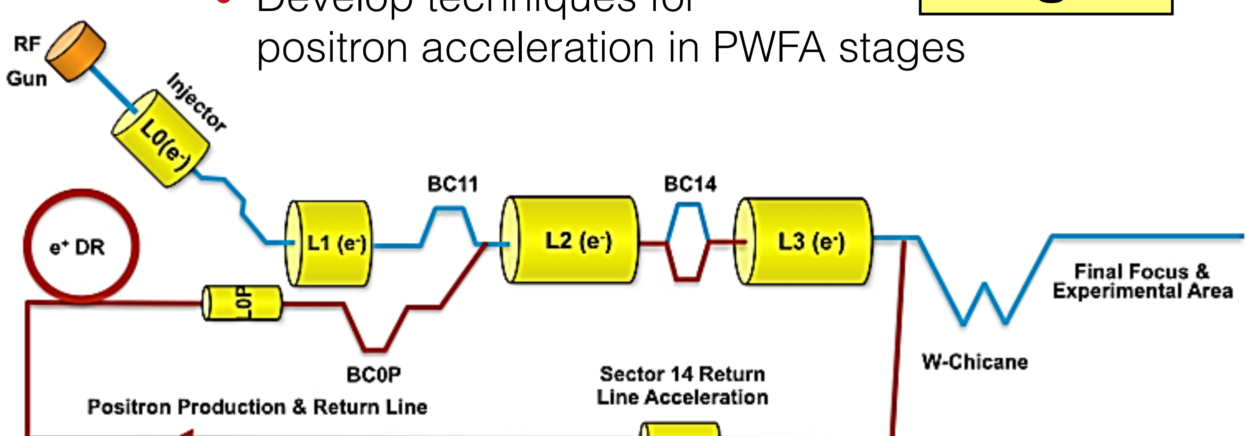


Stage 1

Positron Acceleration
FY21-24

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

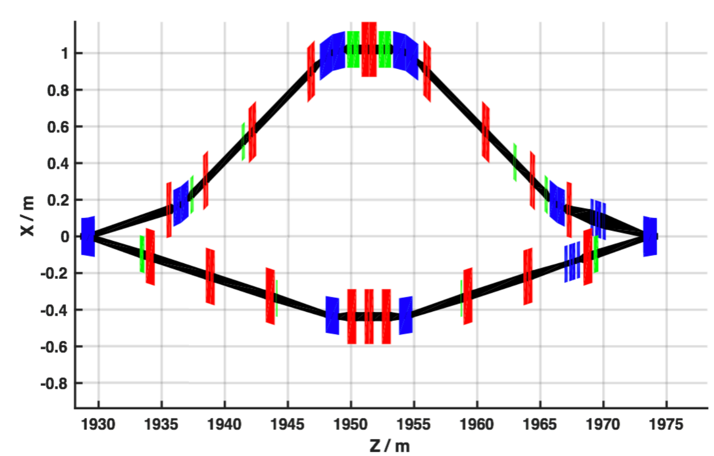
Stage 2

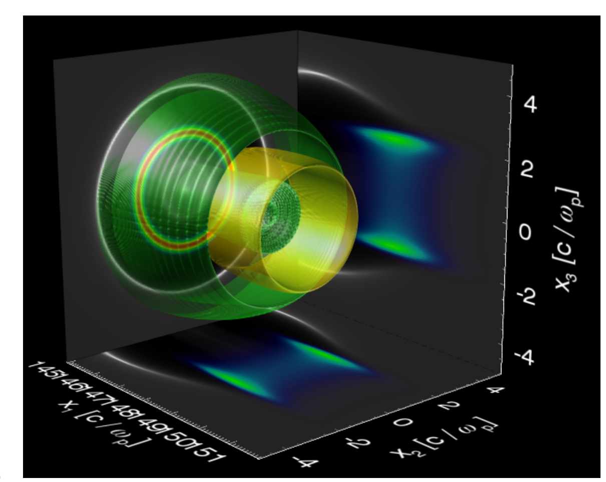


Simultaneous Deliver of Electrons & Positrons
FY22-25

- Positron Acceleration on Electron Beam Driven Wakefields

Stage 3



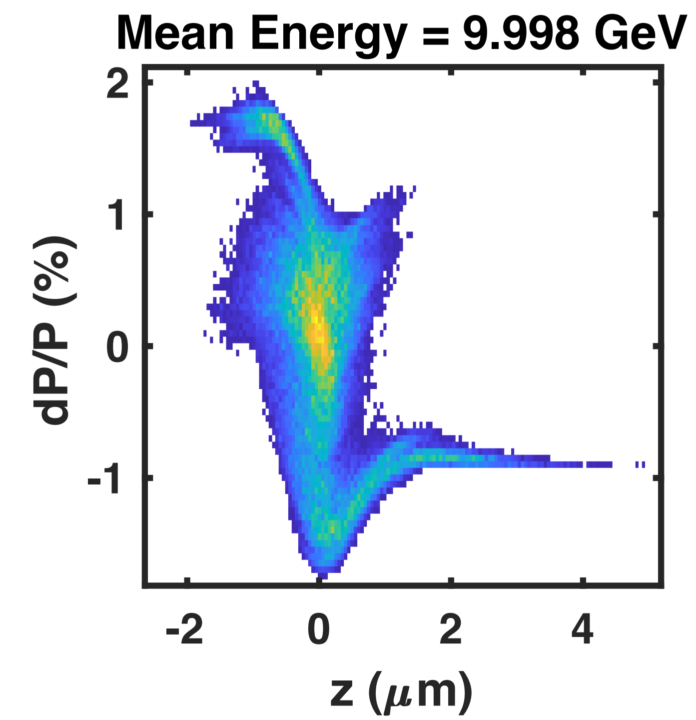


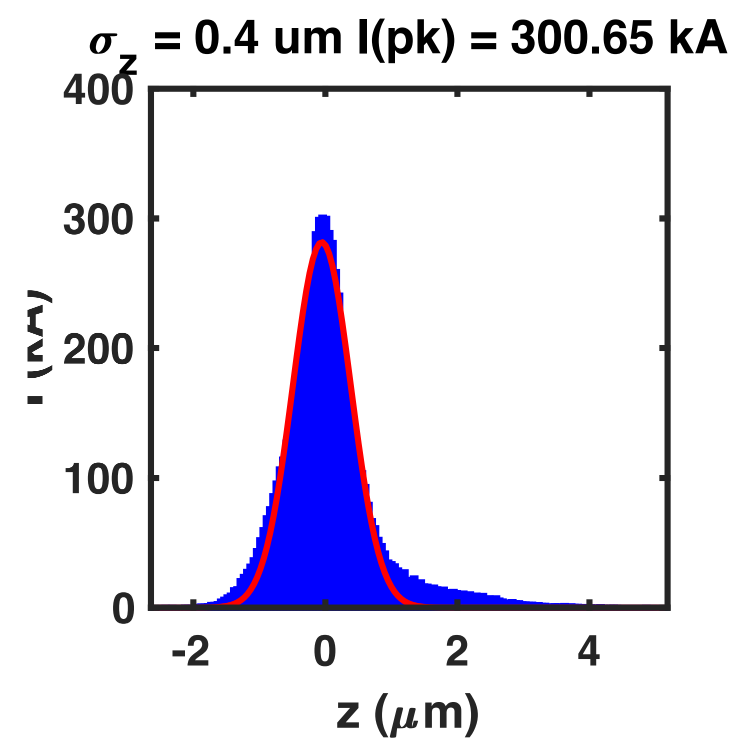
Gradual introduction of capabilities works well with level of demand for FACET-II

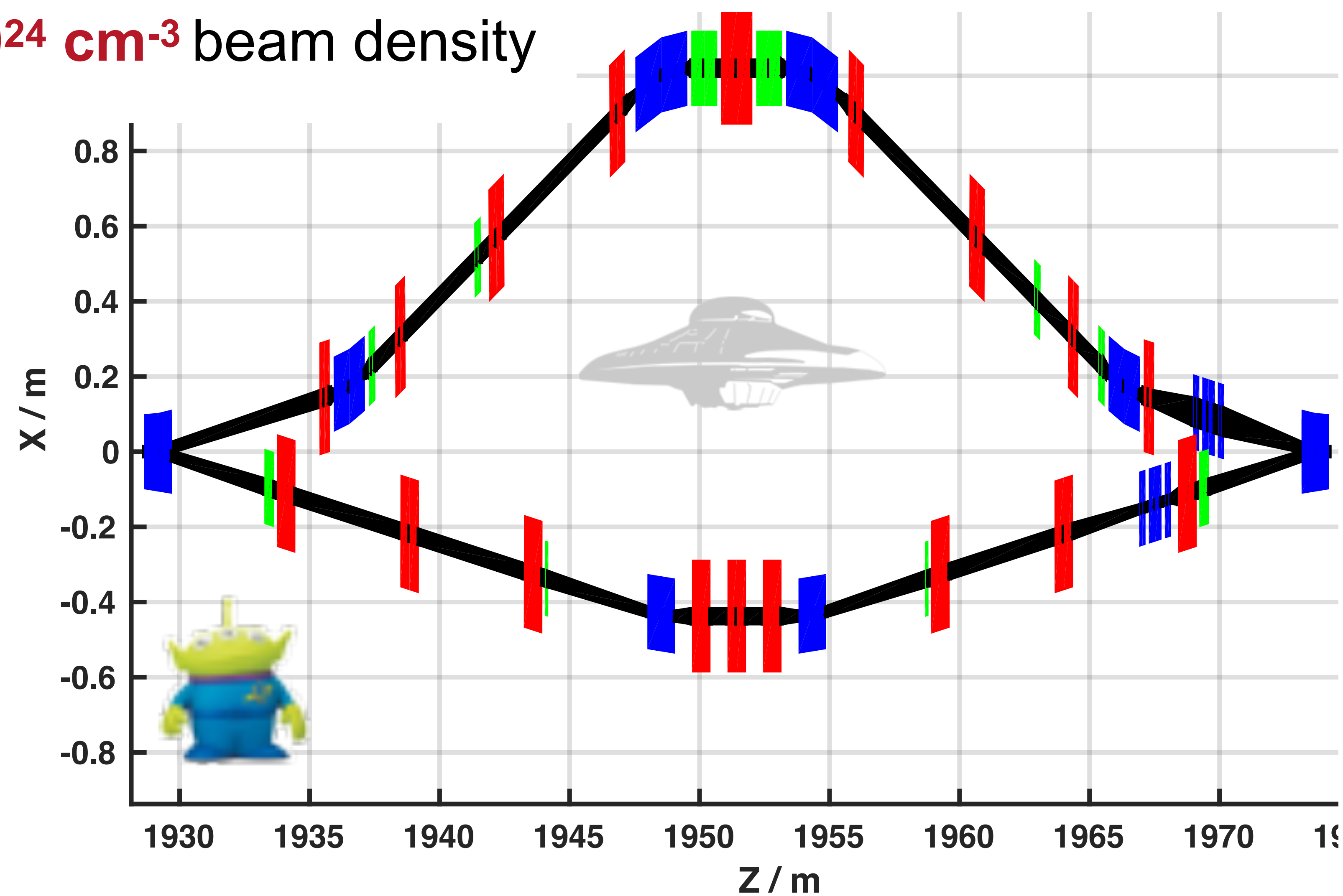
FACET-II Beam will Access New Regimes

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

- >300 kA peak current (~0.4 μm long)
- ~100 nm focus by plasma ion column
- **~10^{12} V/cm** radial electric field (Es=1.3×10^{16} V/cm)
- **~10^{24} cm^{-3}** beam density







Differential pumping at FACET-II

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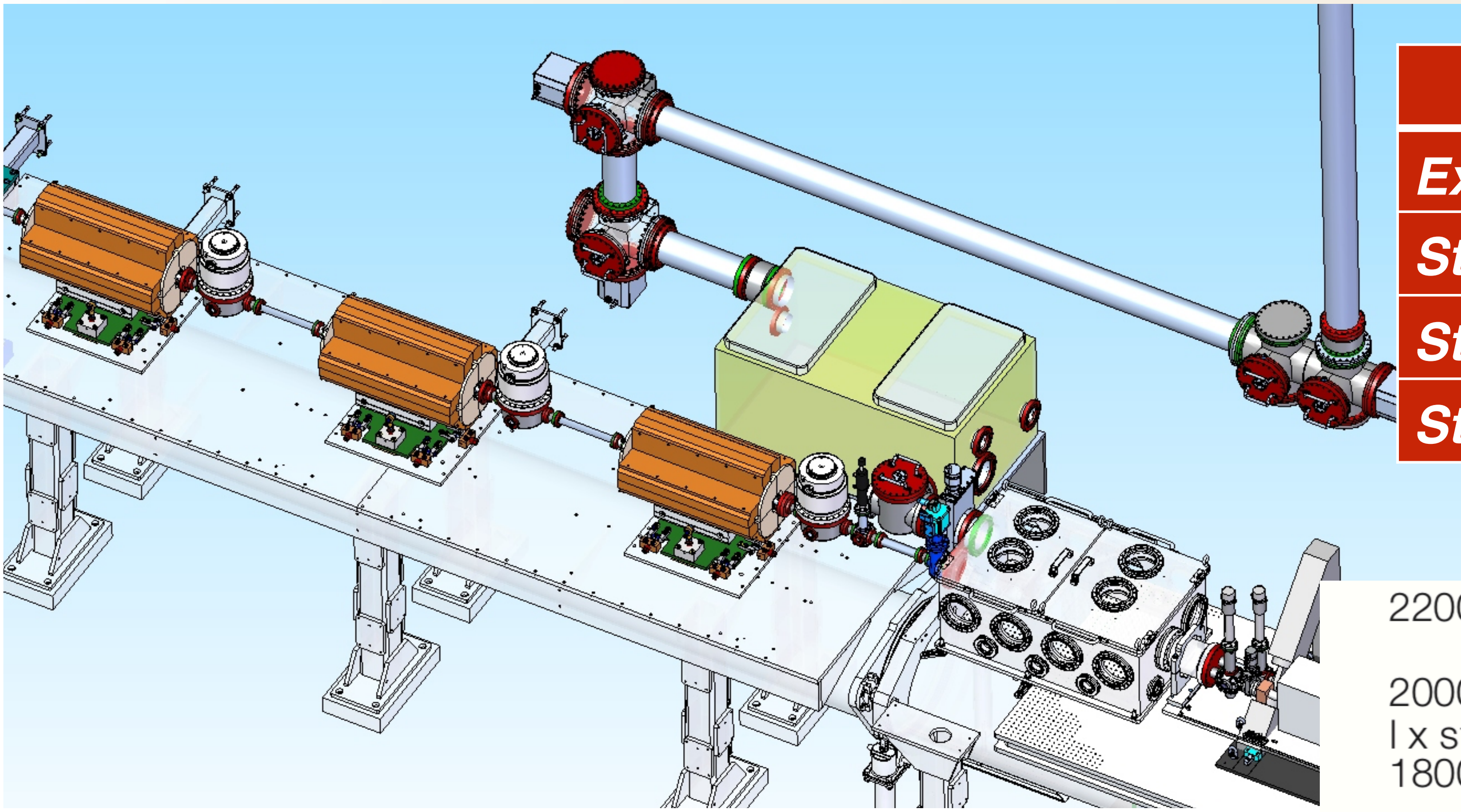
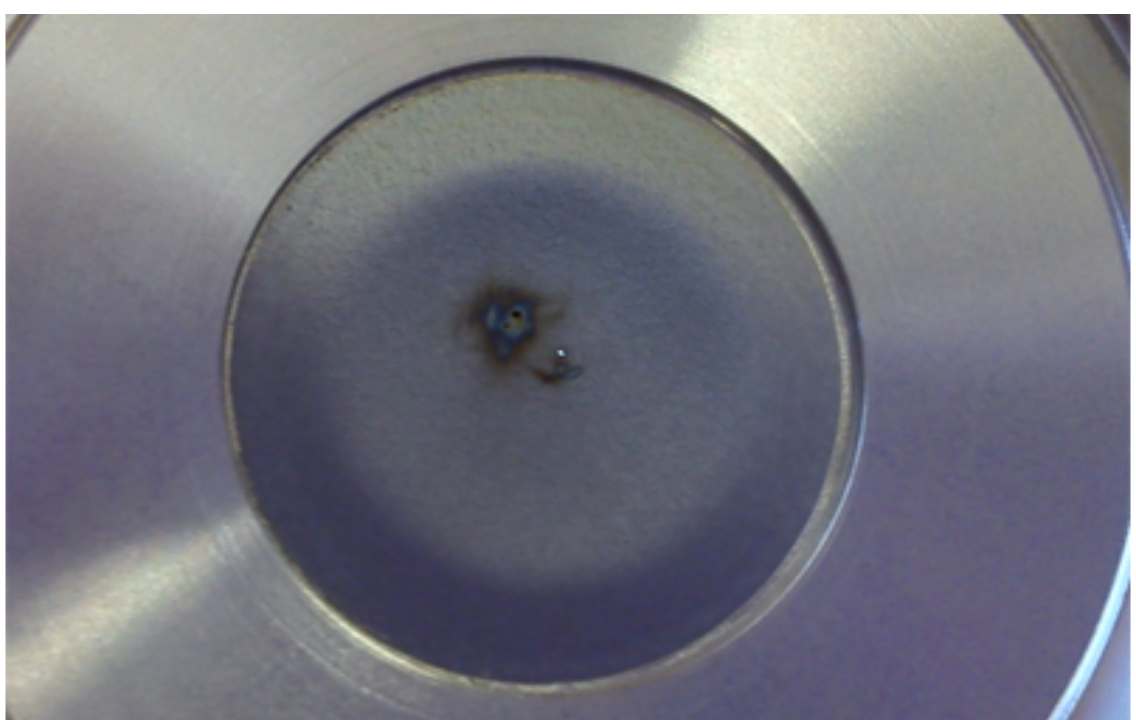
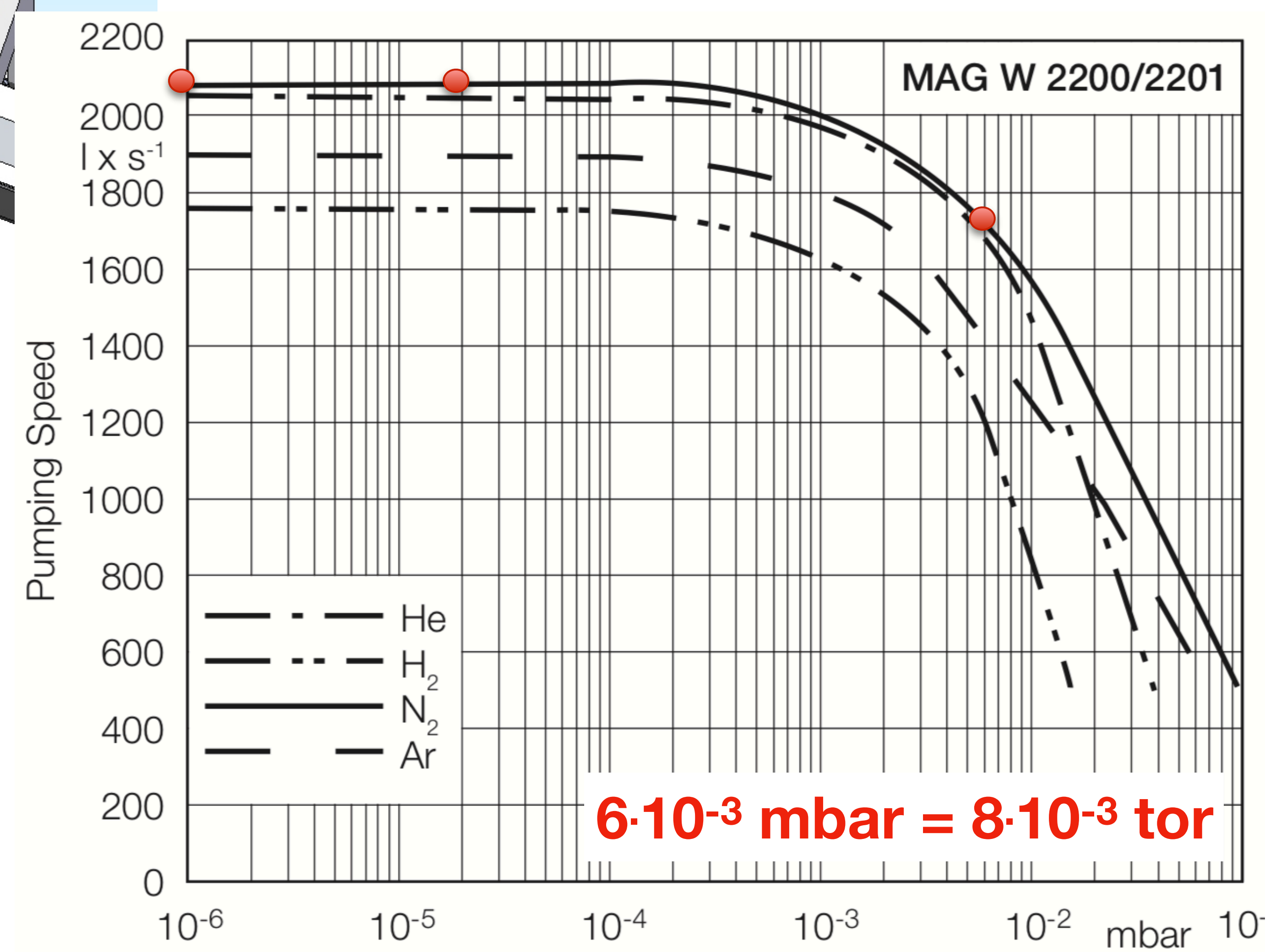


	D [cm]	L[cm]	C [l/s]	S [l/s]	P [torr]
Experiment					5
Stage 1	0.5	10	2.5	1600	7.8E-03
Stage 2	1.8	70	3.8	2200	1.4E-05
Stage 3	1.8	70	3.8	2200	2.4E-08

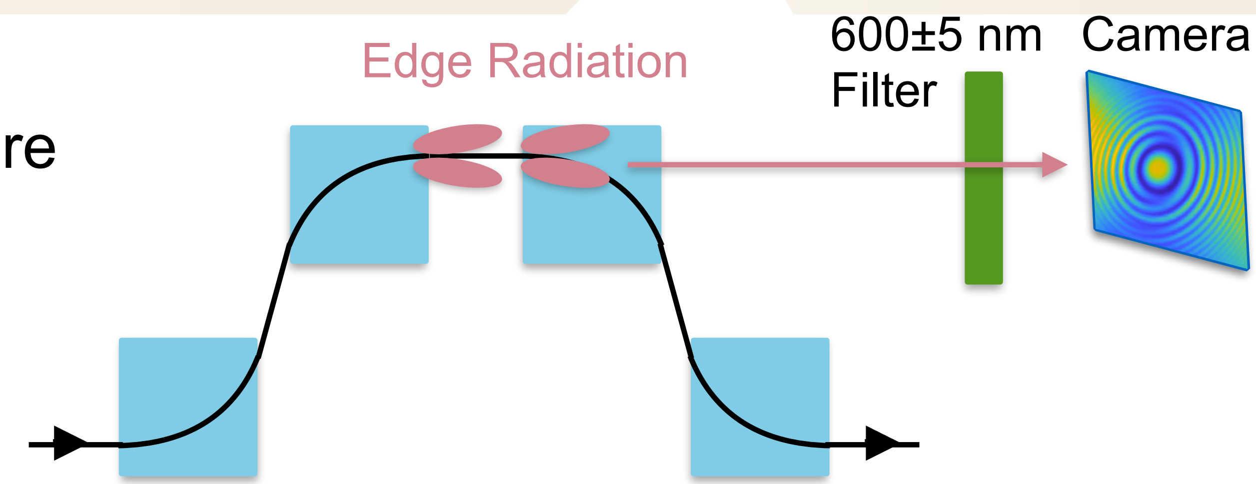
Beam line window with hole from FACET beam

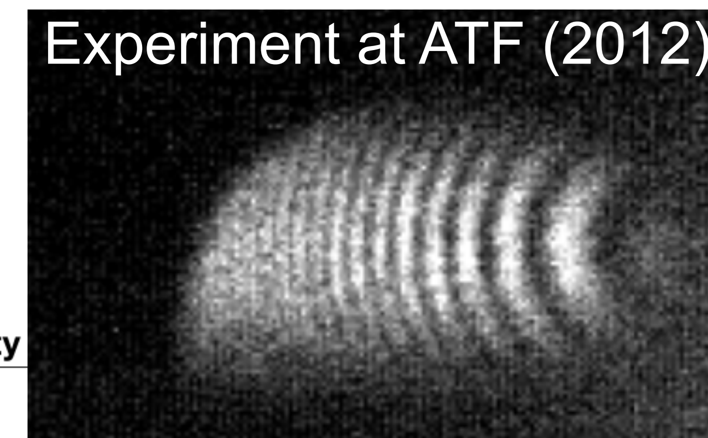


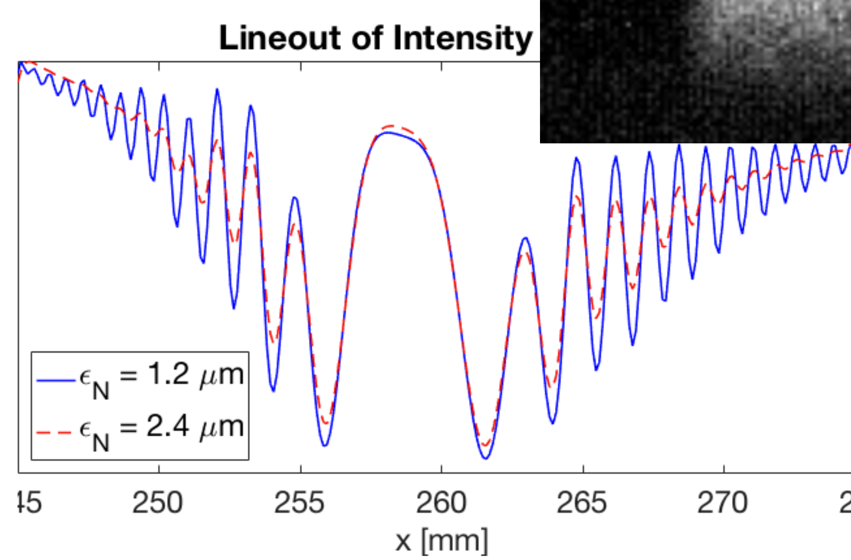


Edge Radiation Beam Diagnostic

- Interference between Edge Radiation (generated at magnet edges) used to measure divergence and energy spread
- Analogous to 1801 Young's Double-Slit experiment:
  - Two edges as sources
  - Beam divergence blur interference patterns
  - Different parts of chicane sensitive to different beam parameters
- Ideal for ***extreme intensity beams*** and computer control (***Machine Learning***)
  - Non-destructive







Non-destructive and single shot nature makes it ideal for extreme intensity beams at FACET-II

Strong-Field QED in Laboratory Experiments

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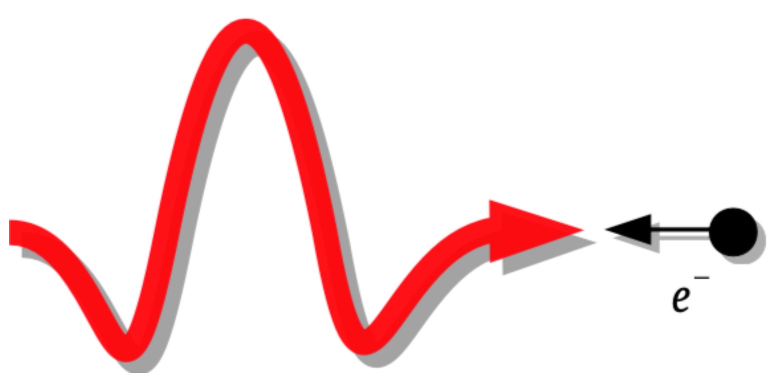
- Critical Field $E_{cr} \approx 10^{18}\ V/m$ Critical Intensity $I_{cr} \approx 4.6 \times 10^{29}\ W/cm^2$
- Decisive Measure: electric field in the particle rest frame (E^*):

$$\chi = \frac{\sqrt{pF^2p}}{E_{cr}mc^2} = \frac{\varepsilon}{mc^2}\frac{E}{E_{cr}} = \frac{E^*}{E_{cr}}$$

K. Yokoya and P. Chen, Frontiers of Particle Beams, 415–445 (1992)

Electron-laser interaction



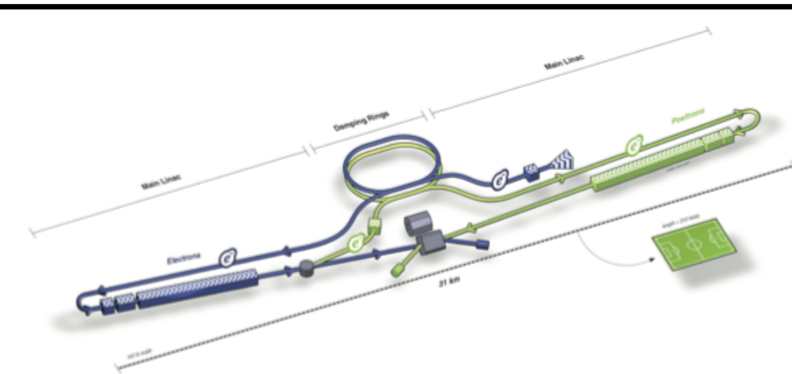
Quantum parameter

$$\chi \approx 0.57 \frac{\varepsilon}{10GeV}\sqrt{\frac{I}{10^{20}W/cm^2}}$$

I: Laser intensity,

ε: electron energy

Beam-beam interaction



Beamstrahlung parameter

$$\chi \approx 0.57 \frac{\varepsilon}{mc^2}\frac{2Nr_e^2}{\alpha\sigma_z(\sigma_x+\sigma_y)}$$

N: Number of particles,

ε: particle energy, $\sigma_{x,y,z}$:

dimensions of the bunch

Intuitive explanation of the Non-perturbative strong field QED collider parameters

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Key challenge: radiative energy loss in field transition (if $\chi \gtrsim 1$) prevents reaching $\chi \gg 1$

- Four (main) beam parameters: transverse σ_r and longitudinal σ_z bunch sizes; number of particles per bunch N; Lorentz factor γ
- Lorentz invariance: only $\sigma_z^* = \sigma_z / \gamma$ relevant → three degrees of freedom
- we can simultaneously fulfill three constraints:

Quantum Parameter

$$\chi_{av} \approx \frac{5}{12} \frac{N\alpha ƛ_c^2}{\sigma_r \sigma_z^*}$$

$\boldsymbol{\alpha\chi^{2/3} \gtrsim 1}$

reaching fully non-perturbative regime

Radiation Probability

$$W \approx \alpha \chi_{av}^{2/3} \frac{\sigma_z^*}{ƛ_c}$$

$\boldsymbol{W < 1}$

acceptable radiation loss

Disruption Parameter

$$D \approx \frac{2N\alpha ƛ_c \sigma_z^*}{\sigma_r^2}$$

$\boldsymbol{D < 0.01}$

small disruption

NpQED Collider scale

- $\sigma_z^* \leq ƛ_c$ — $\sigma_z \lesssim 100nm$ @ $100GeV$
- $N \geq \frac{1}{\alpha^4} \sim 10^9$ — I.e., $\gtrsim$ 100 pC per bunch
- $\sigma_r \sim 10\sqrt{N\alpha}ƛ \approx 10nm$

V. Yakimenko et al. Phys. Rev. Lett. 122, 190404 (2019)

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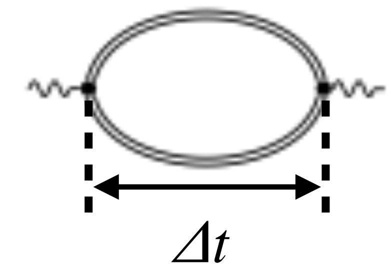
Fully non-perturbative QED: intuitive picture

An electric field E introduces a new mass scale $m_\gamma^2(\chi) \sim \alpha M^2$, $M \sim eE\Delta t / c$, where Δt *is characteristic time scale of quantum fluctuations*

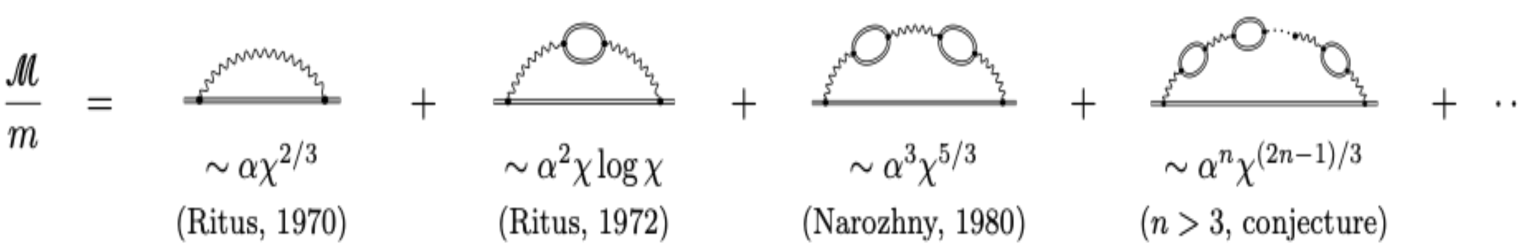
The lifetime Heisenberg uncertainty principle: $\Delta t \Delta\varepsilon \sim \hbar$; $\Delta\varepsilon \sim (eE\Delta t/c)^2 / (\hbar\omega_\gamma)^2$



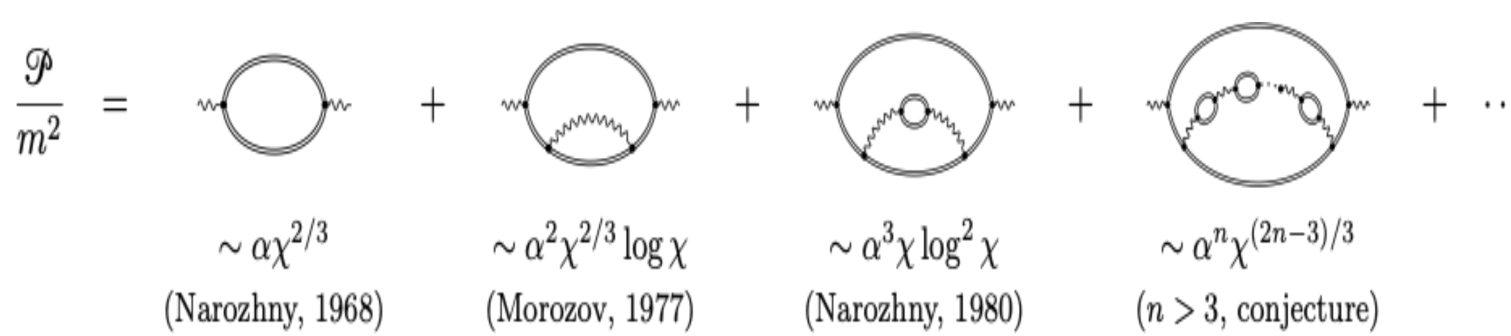
is obtained by comparing $\varepsilon = pc$ (photons) and $\varepsilon = [(pc)^2+m^2c^4+ (eE\Delta t/c)^2]^{1/2} \sim pc + (eE\Delta t/c)^2/(2pc)$ *(pair particles)*

The resulting field-induced mass scale $M \sim m\chi^{1/3}$ **independent of** m (note, $\chi \sim m^{-1/3}$), $m_\gamma(\chi) = \alpha\chi^{2/3} m$: **breakdown of perturbation theory when** $\alpha\chi^{2/3} \gtrsim 1$ **or** $m_\gamma(\chi) > m$

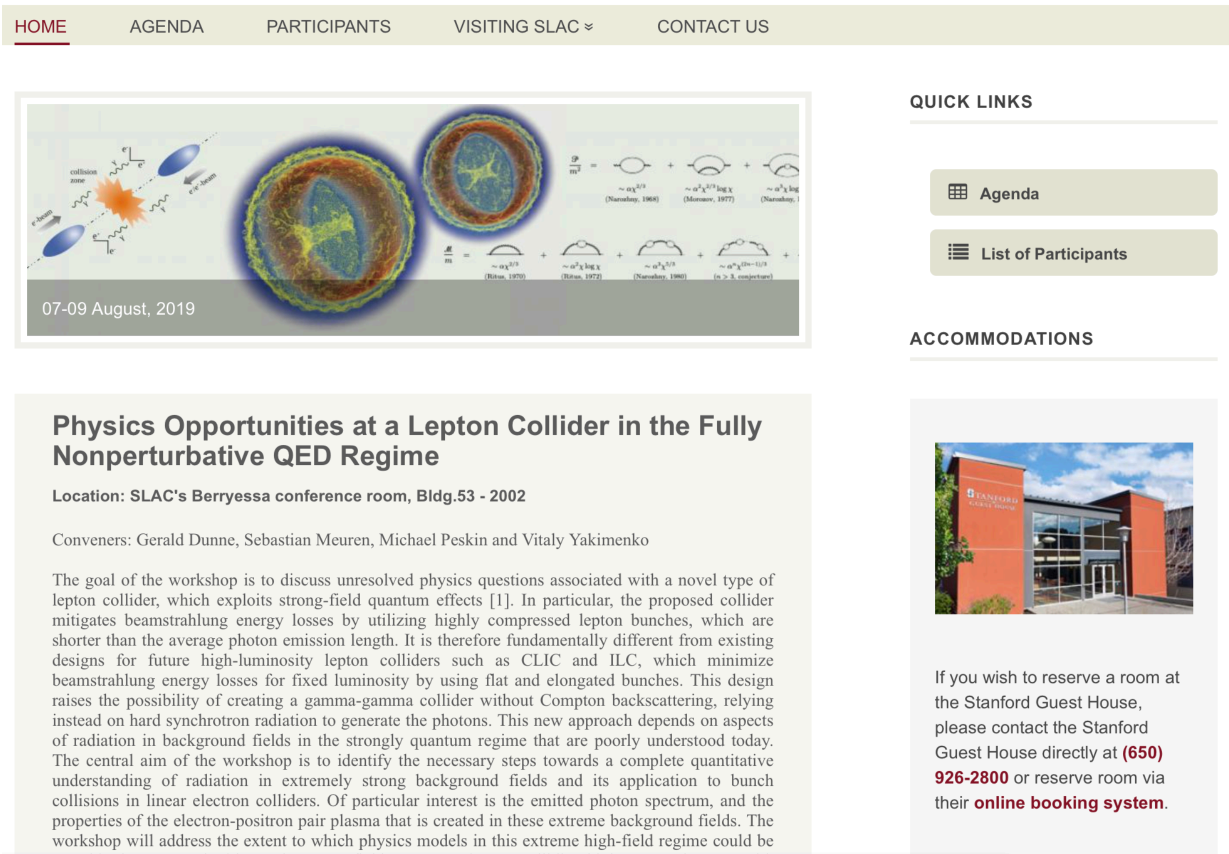
Scaling of diagrams considered so far



A. M. Fedotov, J. Phys.: Conf. Ser. 826, 012027 (2017);
N. B. Narozhny, Phys. Rev. D 21, 1176–1183 (1980);
V. I. Ritus, Ann. Phys. 69, 555–582 (1972)



Workshop on Physics Opportunities in a novel regime of colliding lepton beams in the presence of extreme fields



HOME AGENDA PARTICIPANTS VISITING SLAC CONTACT US

07-09 August, 2019

QUICK LINKS

Agenda

List of Participants

ACCOMMODATIONS

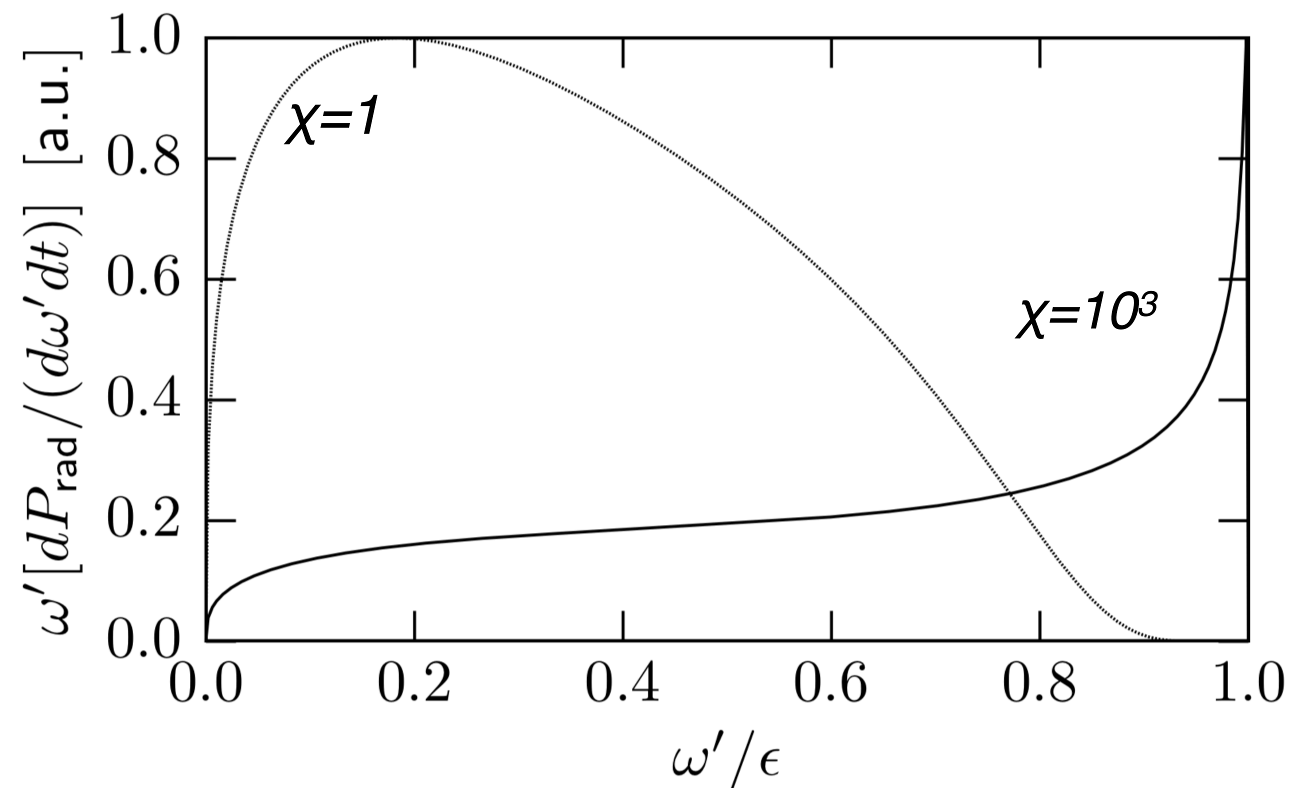
If you wish to reserve a room at the Stanford Guest House, please contact the Stanford Guest House directly at (650) 926-2800 or reserve room via their online booking system.

Physics Opportunities at a Lepton Collider in the Fully Nonperturbative QED Regime

Location: SLAC's Berryessa conference room, Bldg.53 - 2002

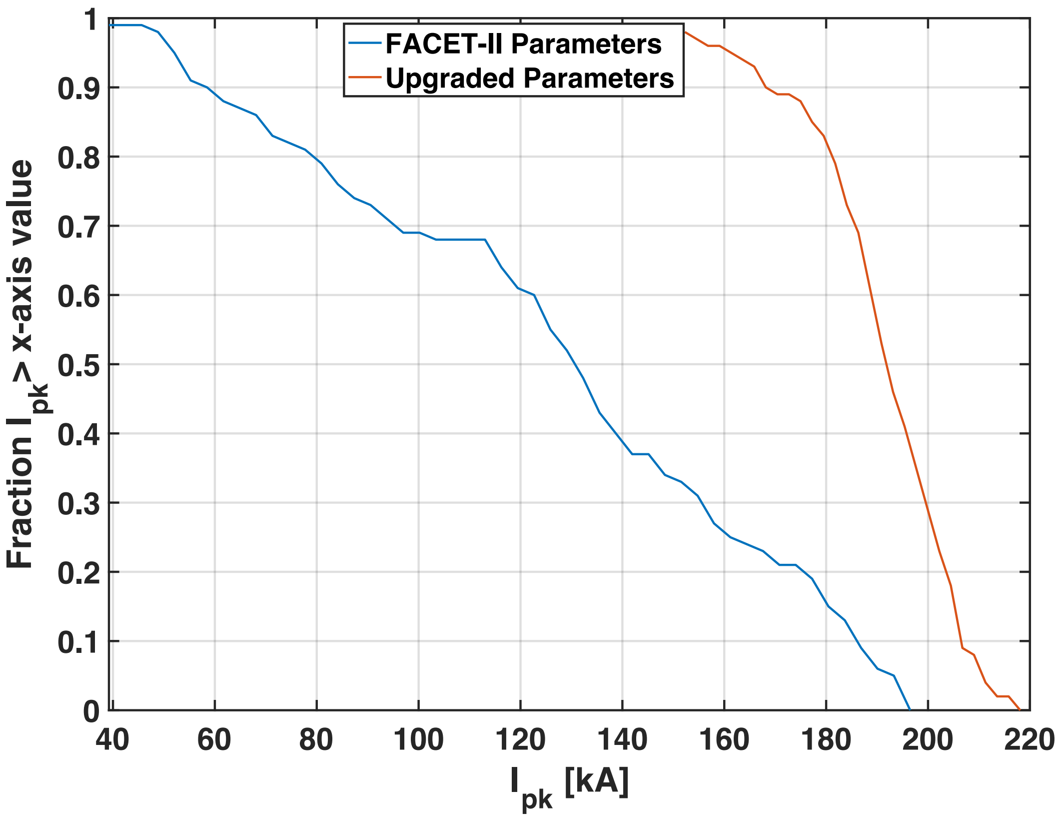
Conveners: Gerald Dunne, Sebastian Meuren, Michael Peskin and Vitaly Yakimenko

The goal of the workshop is to discuss unresolved physics questions associated with a novel type of lepton collider, which exploits strong-field quantum effects [1]. In particular, the proposed collider mitigates beamstrahlung energy losses by utilizing highly compressed lepton bunches, which are shorter than the average photon emission length. It is therefore fundamentally different from existing designs for future high-luminosity lepton colliders such as CLIC and ILC, which minimize beamstrahlung energy losses for fixed luminosity by using flat and elongated bunches. This design raises the possibility of creating a gamma-gamma collider without Compton backscattering, relying instead on hard synchrotron radiation to generate the photons. This new approach depends on aspects of radiation in background fields in the strongly quantum regime that are poorly understood today. The central aim of the workshop is to identify the necessary steps towards a complete quantitative understanding of radiation in extremely strong background fields and its application to bunch collisions in linear electron colliders. Of particular interest is the emitted photon spectrum, and the properties of the electron-positron pair plasma that is created in these extreme background fields. The workshop will address the extent to which physics models in this extreme high-field regime could be



- Determine which particle physics questions could be studied with such collider and at which energy scale. In particular, the question whether an 100 GeV-scale electron-electron collider could efficiently probe s-channel Higgs resonances via hard gamma-gamma collisions.
- Investigate the possibility to utilize electron-electron collisions in strong field regime to realize a gamma-gamma collider: in the extreme quantum regime the electron beam energy can be efficiently converted to high-energy gamma photons via beamstrahlung.
- Clarify the potential of this approach for future multiple-TeV scale collider for the energy frontier of particle physics.

Stability of compression to sub-μm bunches



Approaches to improved stability:

- Alternating sign multi-stage compression (equivalent to FODO focusing concept)
  - Chirpers: off-crest RF, wakefields, IFEL
  - Compressors: ballistic, chicane, dog-leg, zig-zag, wiggler
- High-Q RF (SRF) and resonant enhancement laser cavities for improved phase stability
- Stabilization from self induced wakes (longer bunch => smaller wake induced chirp)
- Correlation between transverse and longitudinal motions at ~100nm scale
- Correct treatment of 3D CSR effects

Applications:

- Beam physics towards new operating regimes in existing and next generation X-FELs (BES)
- Beam physics towards collider with suppressed beamstrahlung (HEP)
- Support for f high brightness beams from Plasma Wakefield (HEP)
- Gamma ray source based filamentation (NNSA)
- High average power UV lithography source (Semiconductor industry)

Goal: Design for ~1GeV, 10nm long bunches (10pC, 1MHz CW)
Understanding stability with codes that are benchmarked with 400nm beams at FACET-II

Conclusion:

We are just starting …