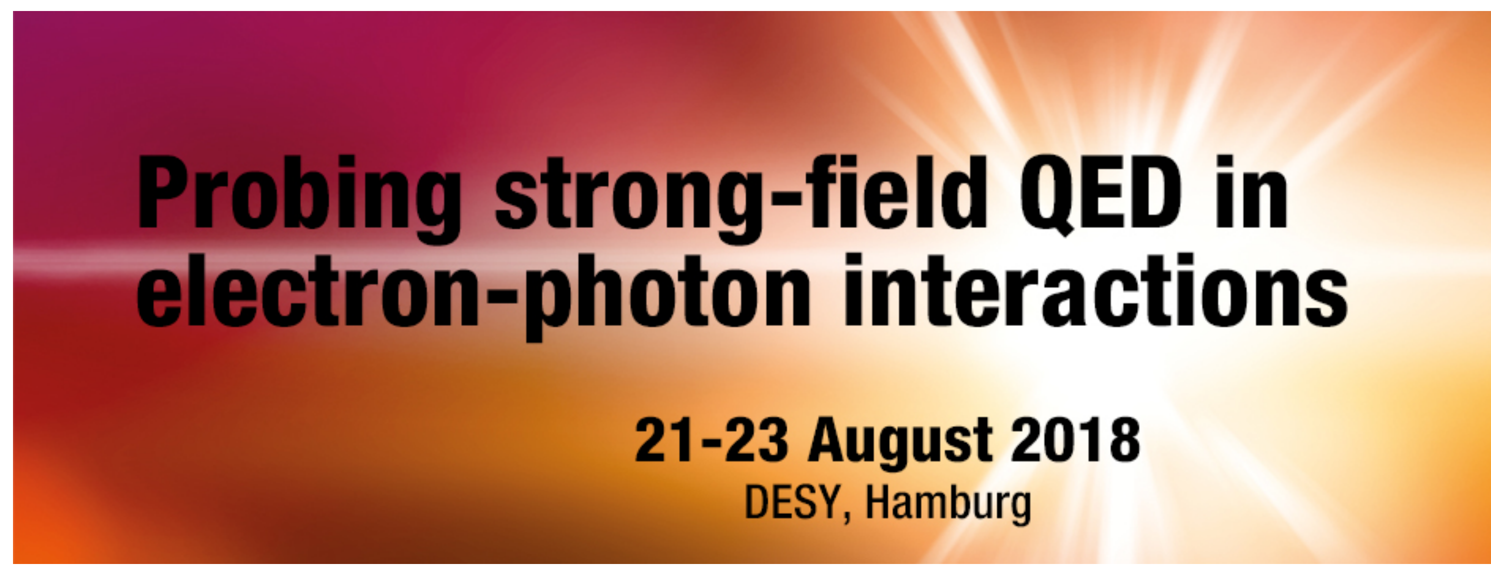
FACET-II | Facility for Advanced Accelerator Experimental Tests

Non perturbative QED science enabled by short electron beams



August 22, 2014

Vitaly Yakimenko

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

The Scale for a TeV Linear Collider

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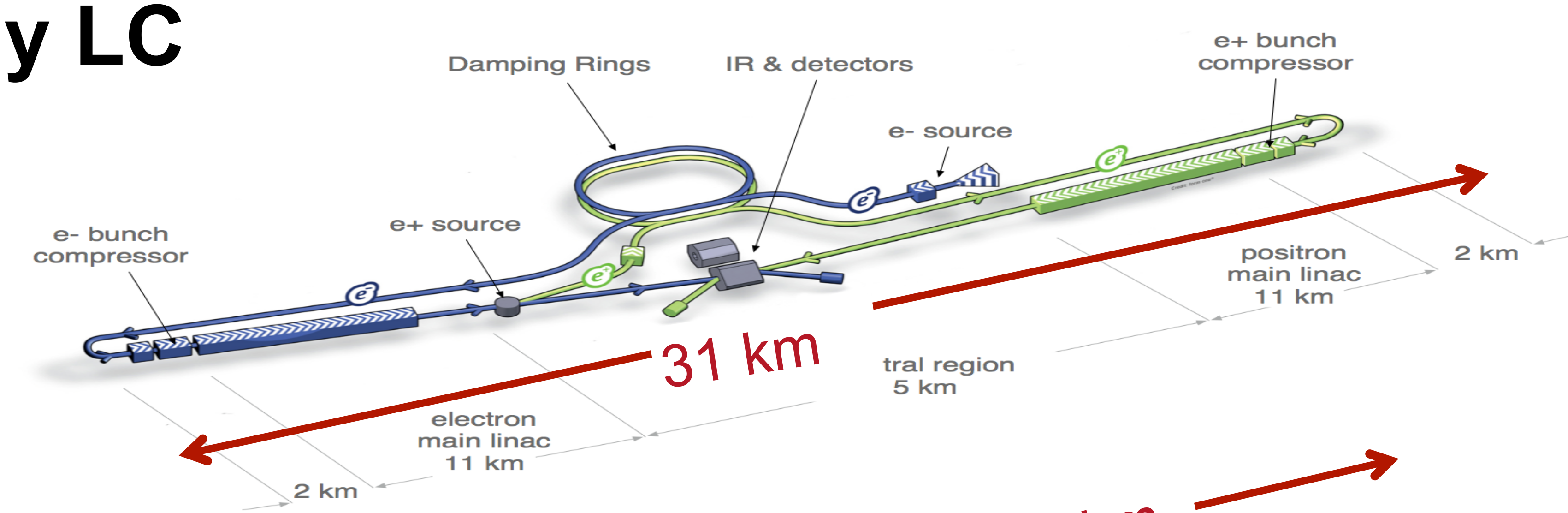
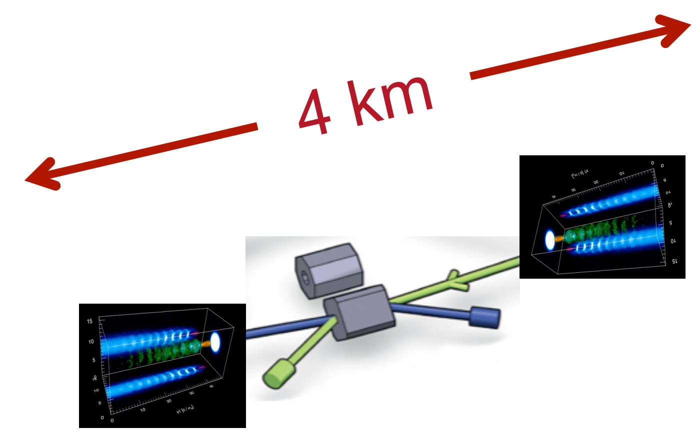
Today's technology LC – a 31km tunnel:



Plasma Wakefield Technology LC:

GeV/m accelerating gradient



The Luminosity Challenge:

High-efficiency and beam quality

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

…and must do it for positrons too!

FACET: A National User Facility based on high-energy beams and their interaction with plasmas and lasers

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
- >200 Users, 25 experiments, 8 months/year operation

Key PWFA Milestones:

√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 review)

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

FACET Celebration Party - April 2016

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

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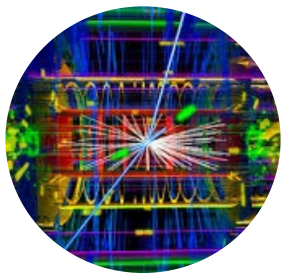
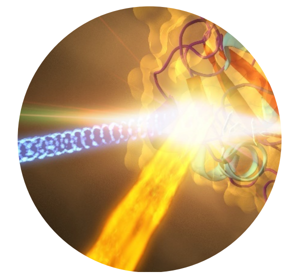
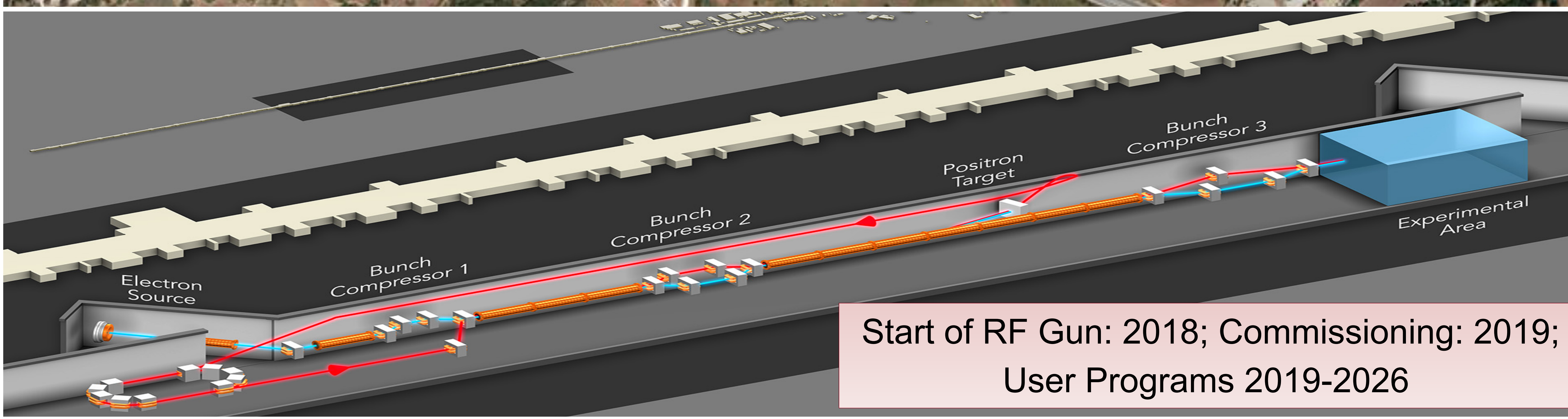


Advance the energy frontier for future colliders



Develop brighter X-rays for photon science

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



Start of RF Gun: 2018; Commissioning: 2019; User Programs 2019-2026

FACET-II Annual Science Opportunities Workshops and First Program Advisory Committee Meeting October 8-12, 2018

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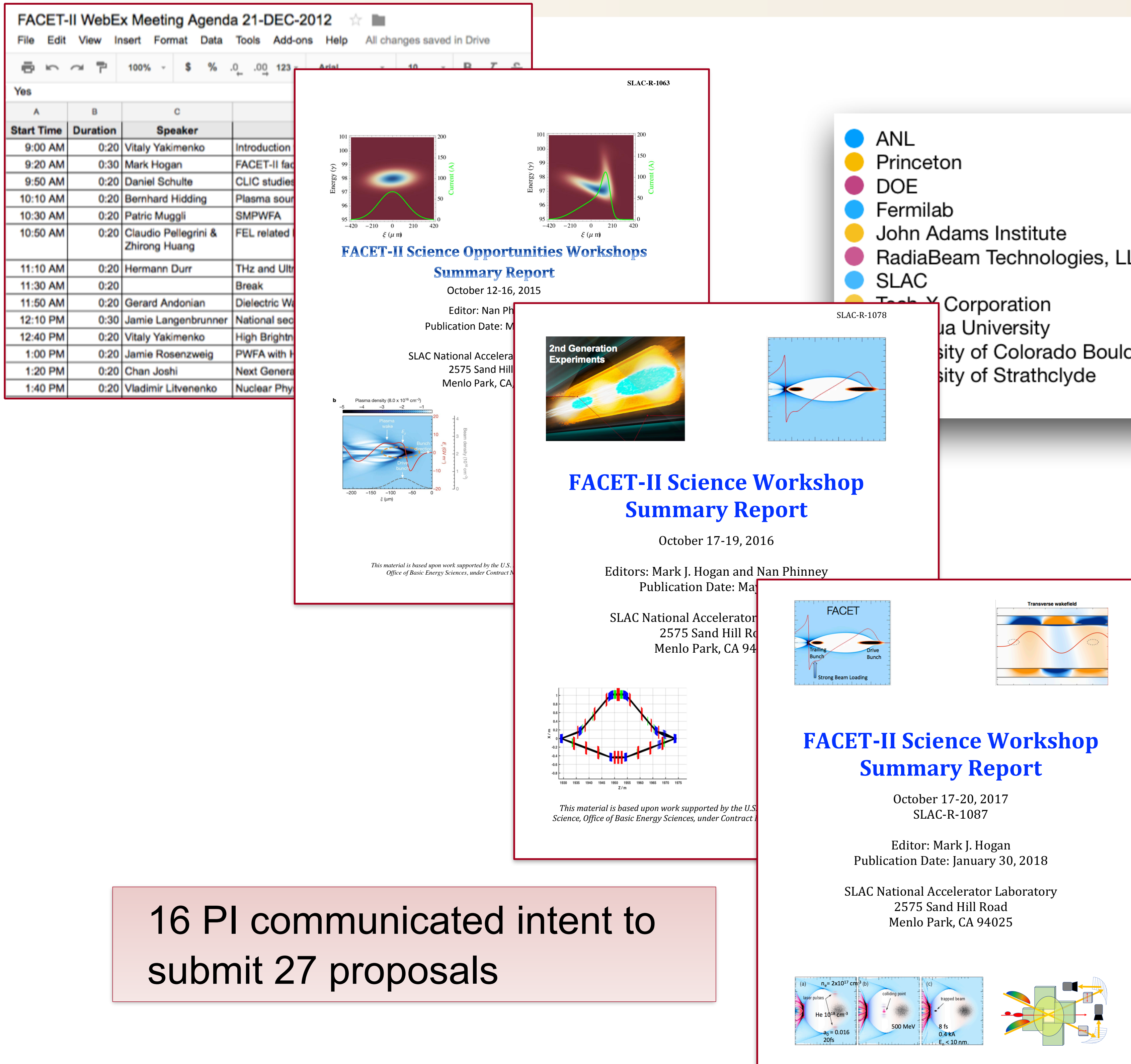

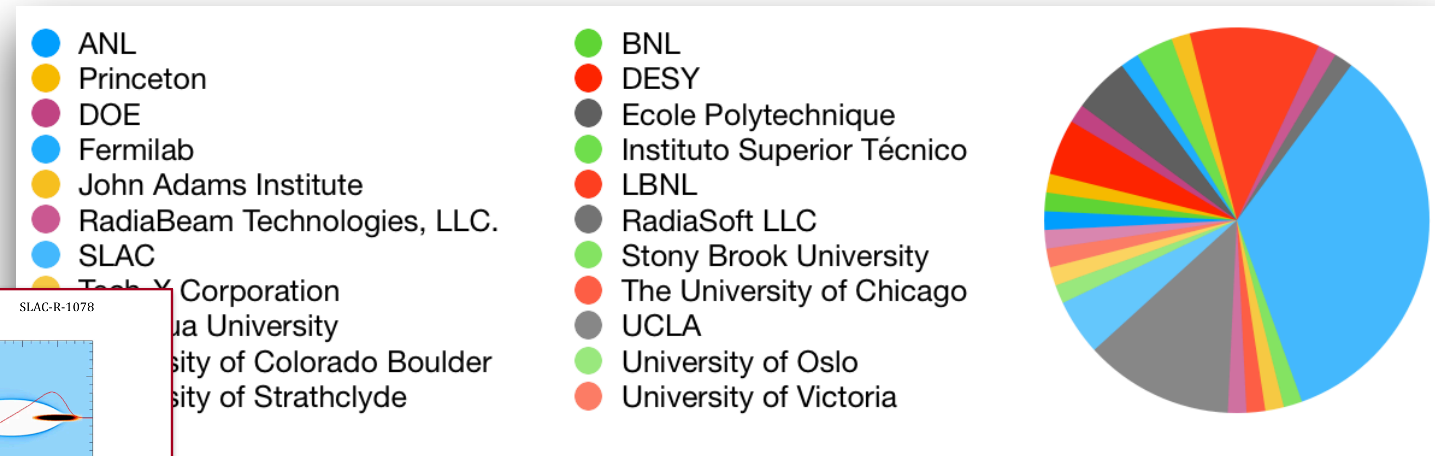

2017 Workshop:
64 Participants
23 Institutions

16 PI communicated intent to submit 27 proposals

User community is engaged with annual science workshops

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

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Key Upgrades:

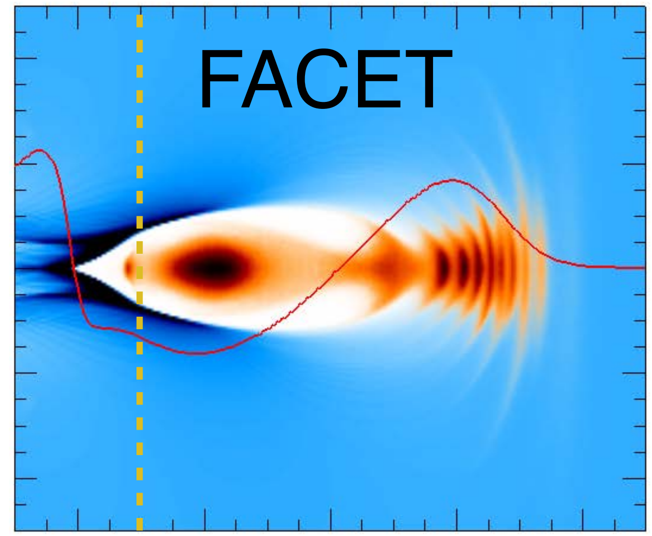
- Photoinjector beam
- Plasma source with matching ramps
- Differential pumping
- Single shot emittance diagnostic

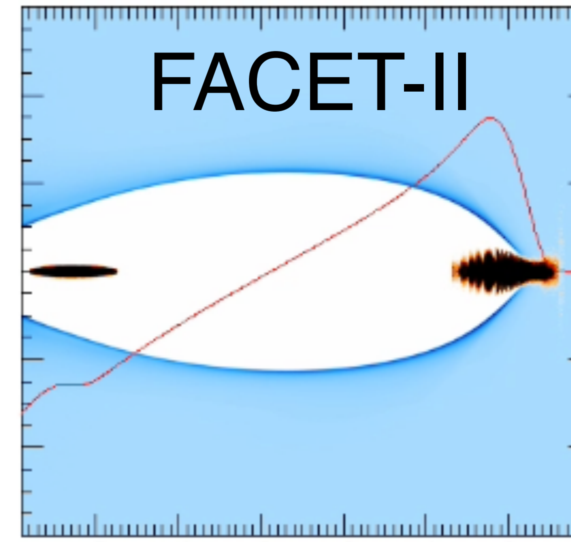
Science deliverables:

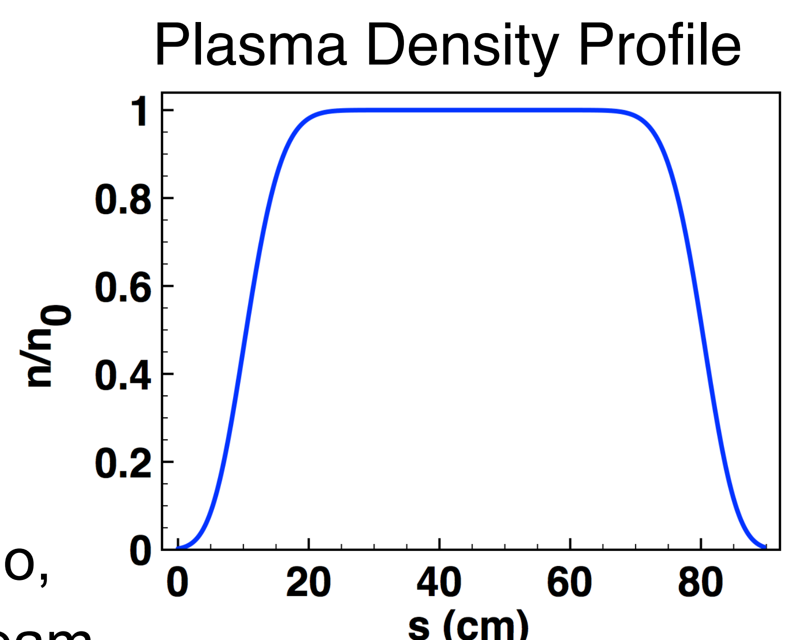
- Pump depletion of drive beam with high efficiency & low energy spread acceleration
- Beam matching and emittance preservation

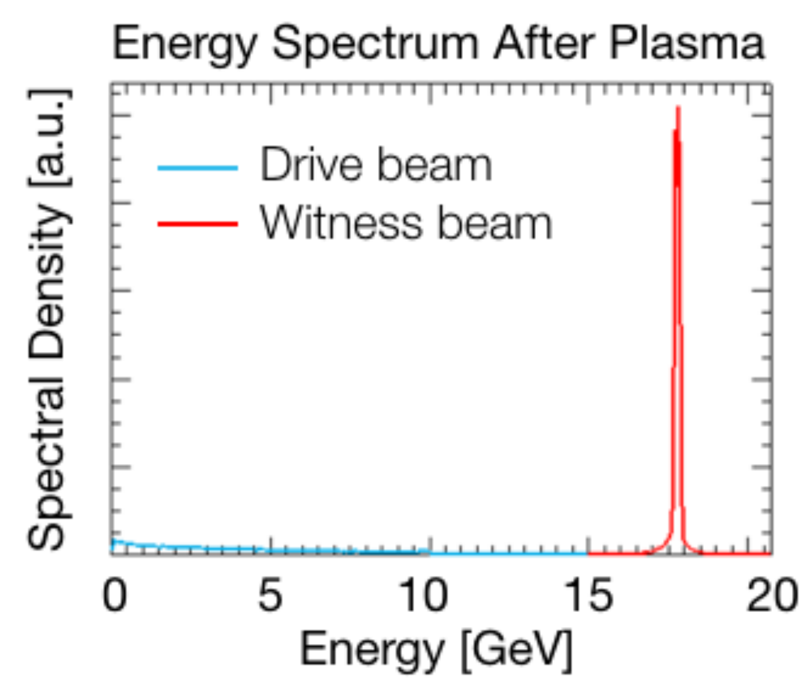
Simulated Performance:

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









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

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

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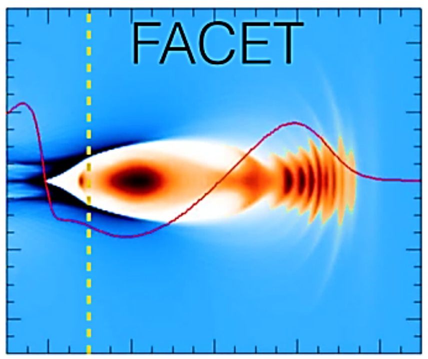
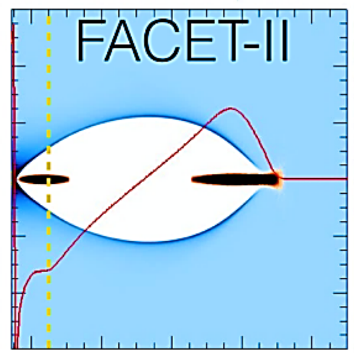
Emittance Preservation with Efficient Acceleration

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

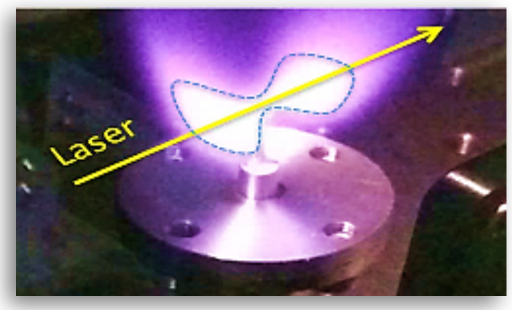


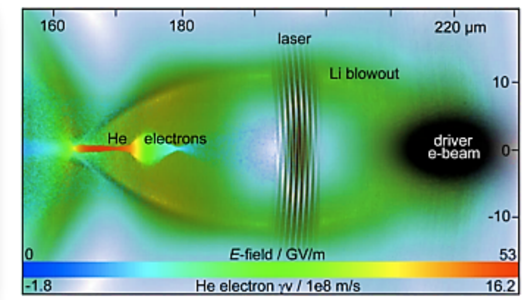


High Brightness Beam Generation & Characterization

FY20-22

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





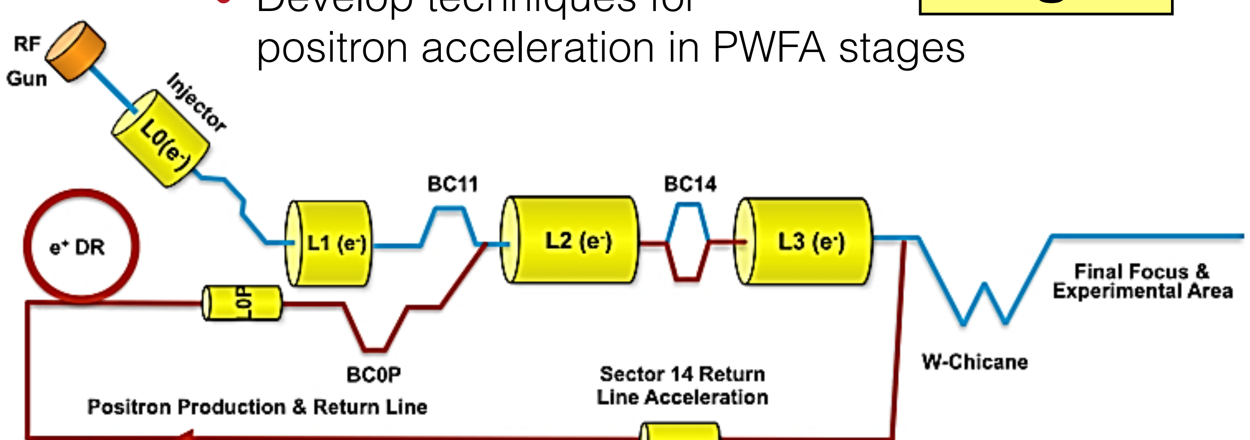
Stage 1

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

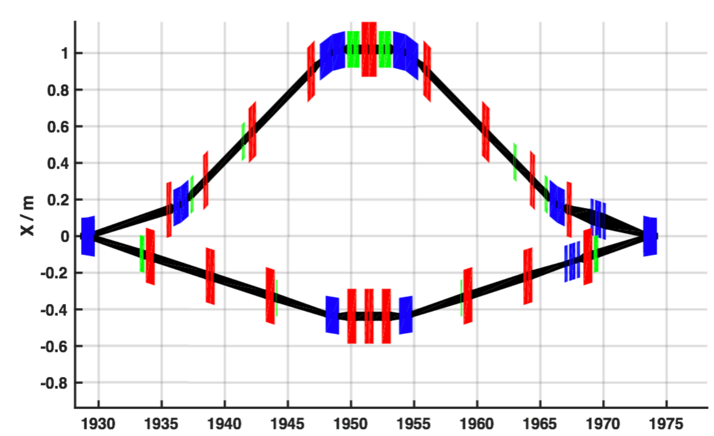


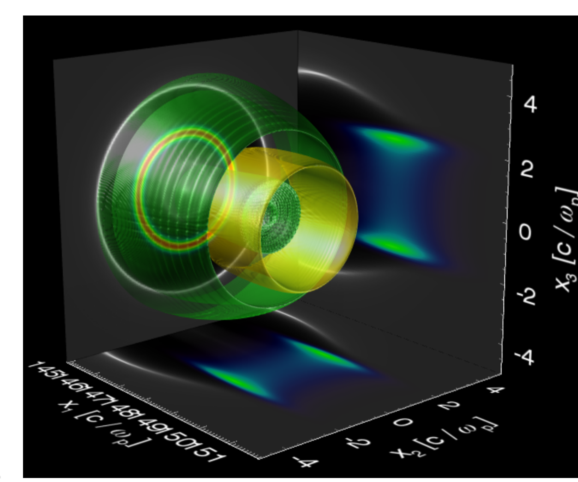
Simultaneous Deliver of Electrons & Positrons

FY22-25

- Positron Acceleration on Electron Beam Driven Wakefields

Stage 3





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

Extreme Beams: A Challenge *and* Opportunity!

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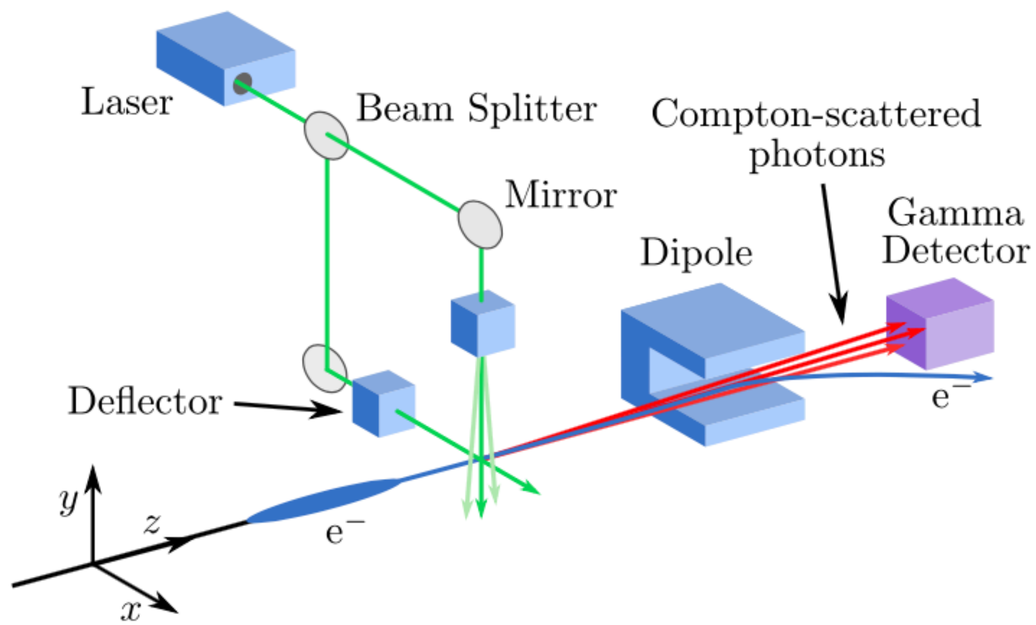
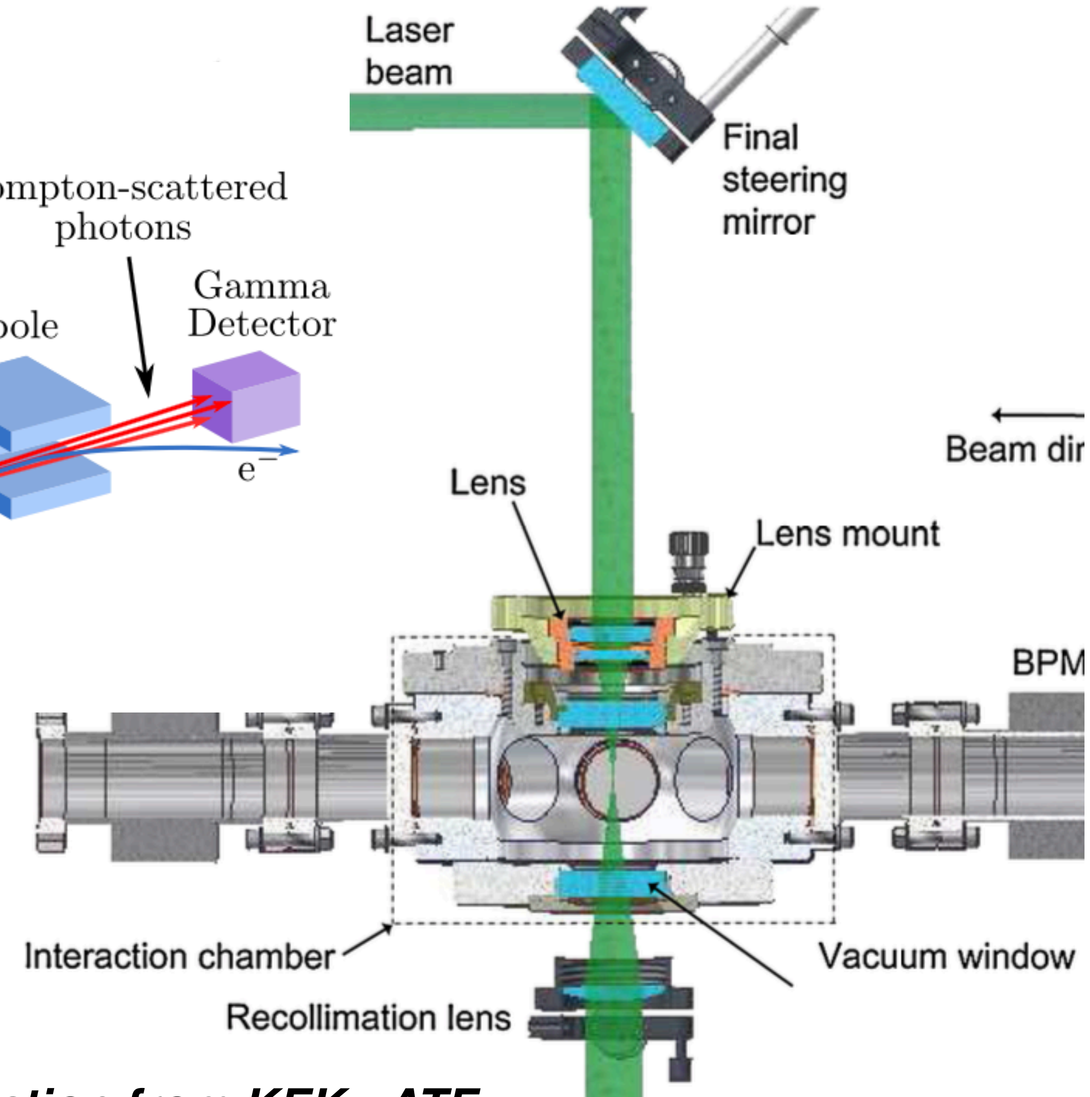
- We know from experience – extreme beam densities developed at FACET and FACET-II turn materials into plasma physics experiments!
- Allows experiments to access new regimes

$$P \propto \frac{Q^2}{\sigma_r^2 \sigma_z^2} F\left({}^{\sigma_r}/_{\sigma_z}\right)$$





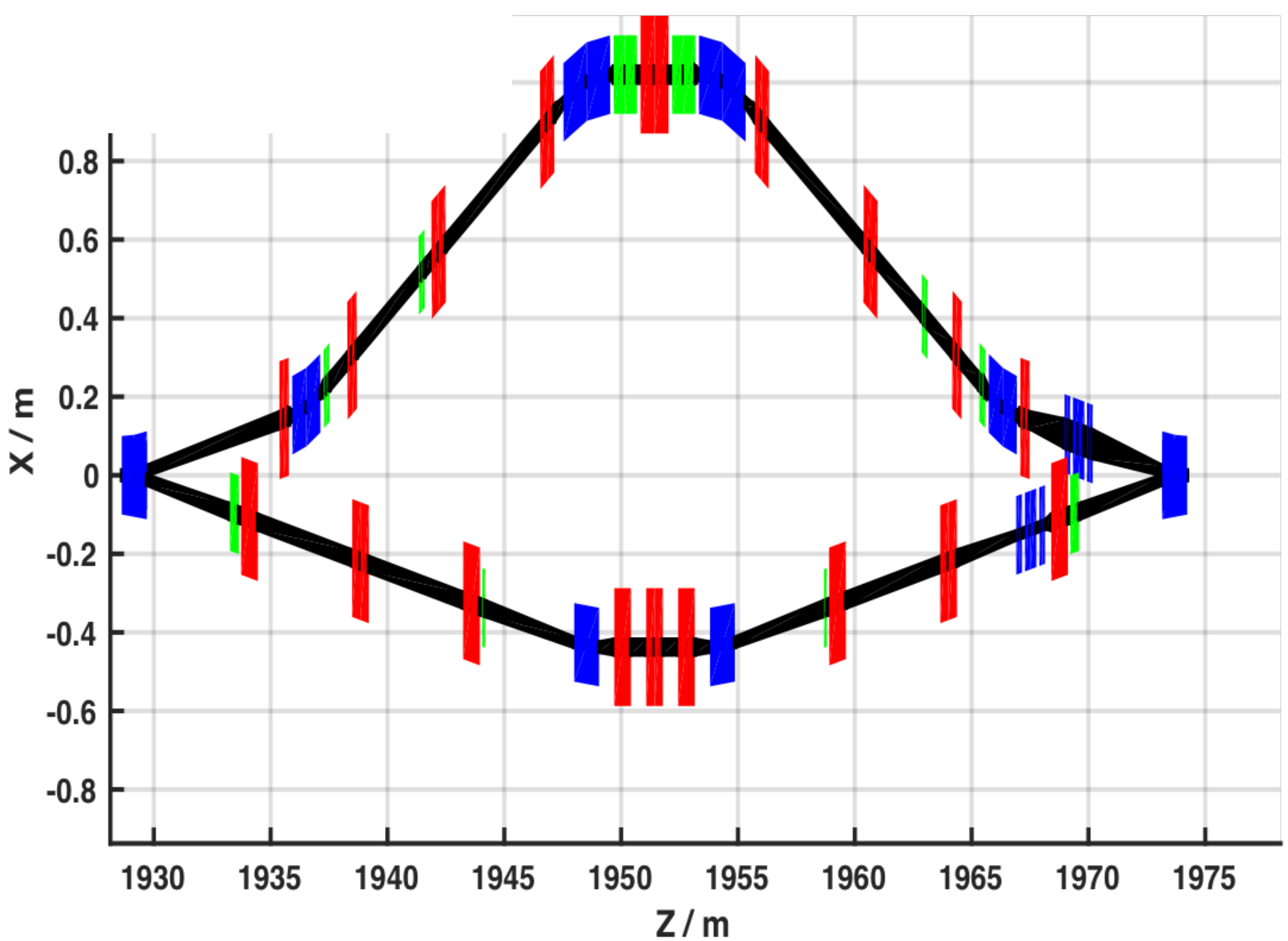
Example installation from KEK - ATF

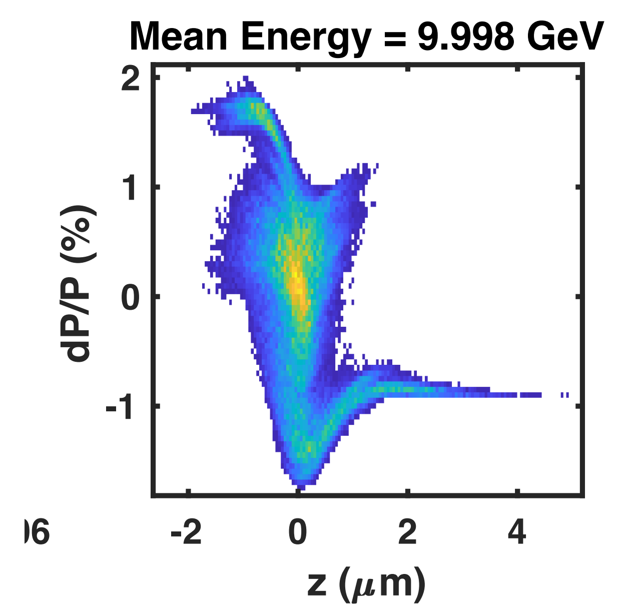
FACET-II will transition from 100 GeV/m to 1-100 TeV/m

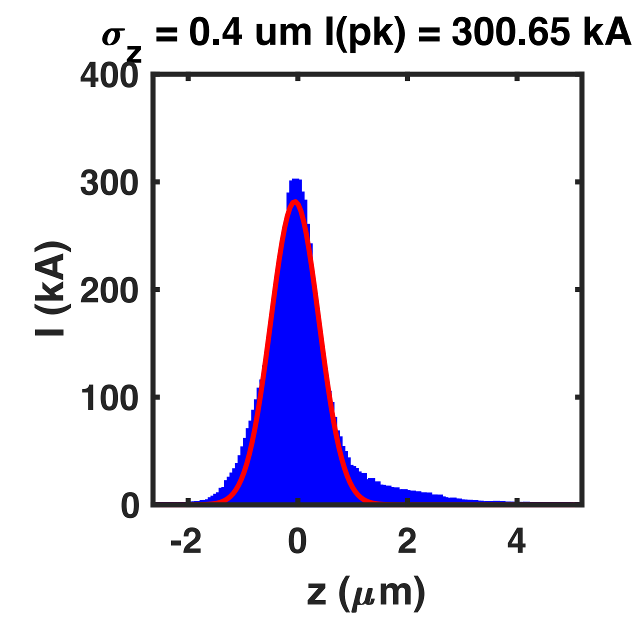
FACET-II Beam will Access New Regimes

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

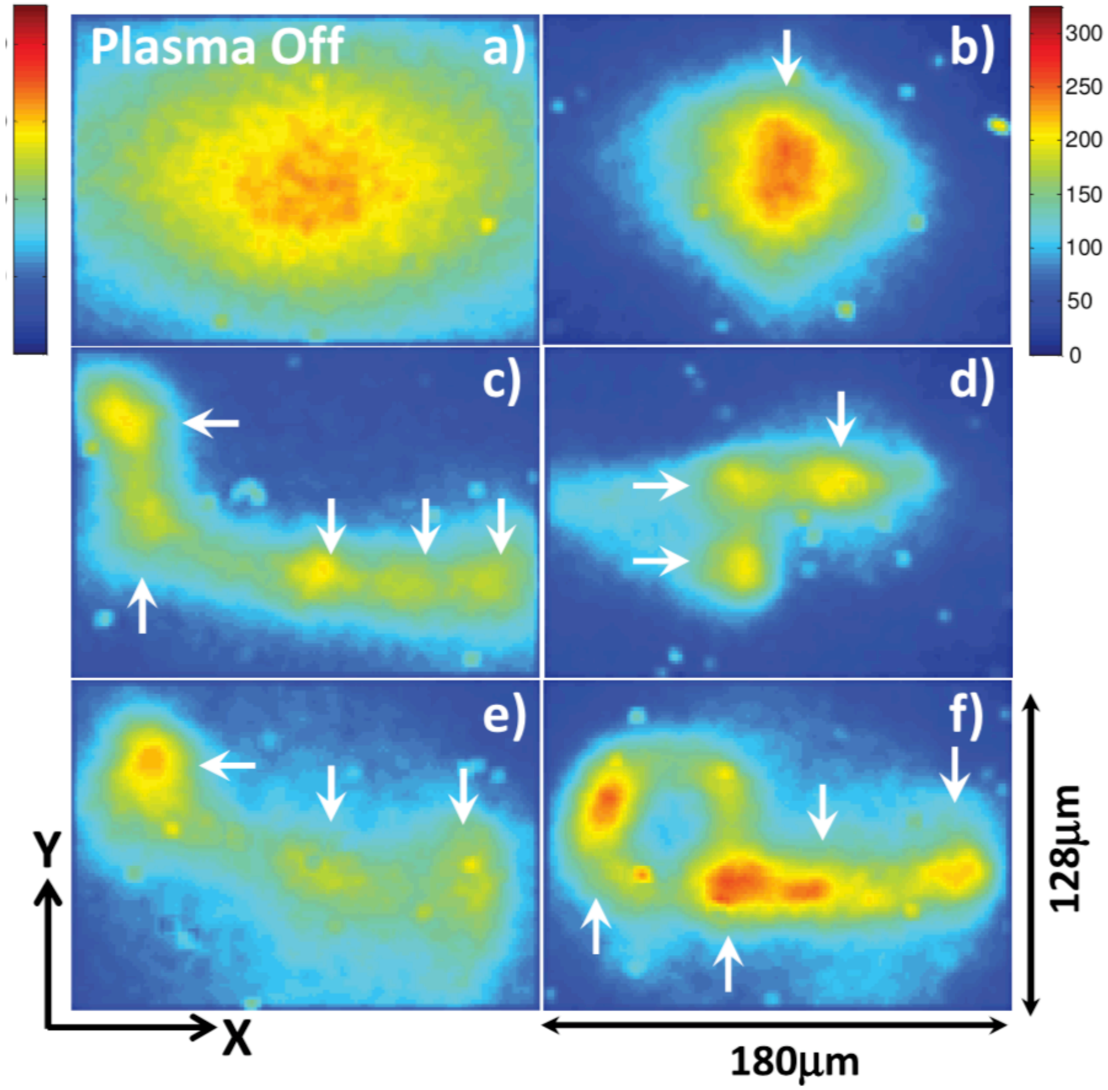
- >300 kA peak current (~0.4 µm long)
- ~100 nm focus by plasma ion column
- **~10^{12} V/cm** radial electric field (Es=1.3x10^{16} V/cm)
- **~10^{24} cm^{-3}** beam densitv



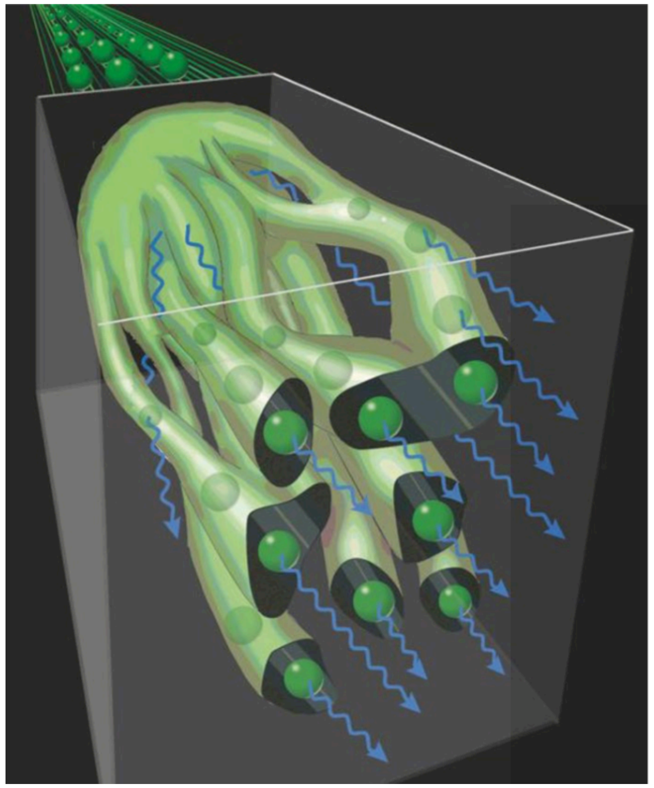




Concept of an electron-beam-instability driven gamma-ray source



A dense bunch of high-energy electrons (green spheres) propagating in a plasma background breaks up into multiple filaments (green tubes) because of an electromagnetic instability, generating superstrong magnetic fields. The individual trajectories of the beam electrons are bent by the magnetic fields, causing synchrotron emission of gamma-ray photons (blue wavelets). *Image courtesy of Max Planck Institute for Nuclear Physics*



Current filamentation instability is observed and studied in a laboratory environment with a 60 MeV electron beam and a plasma capillary discharge. Multiple filaments are observed and imaged transversely at the plasma exit with optical transition radiation.

B. Allen, et.al. Phys. Rev Lett. 2012

A.Benedetti, et.al. Nature Photonics, 2018

ILC Luminosity optimization

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Luminosity: $$L = \frac{P_b}{E_b} \frac{N_b}{4\pi\sigma_x\sigma_y}$$

- Beam Power → P_b
- Beam Energy → E_b
- Number of particles per bunch → N_b
- Area of the beam → $4\pi\sigma_x\sigma_y$

$$L \propto \frac{P_b}{E_b}\sqrt{\frac{\delta_{BS}}{\varepsilon_{ny}}}$$

- Loss of energy associated with beamstrahlung → δ_{BS}
- Normalized vertical emittance → ε_{ny}

Parameter	Symbol [Unit]	ILC (TDR) 250 GeV CM	NpQED Collider [large-σ_z]
Beam Energy	E [GeV]	125	125
Bunch Charge	Q [nC]	**3.2**	**1.4**
Peak Current	I_{pk} [kA]	0.4	1700
rms Bunch Length	σ_z [μm]	**300**	**0.1**
rms Bunch Size	$\sigma^*_{x,y}$ [μm]	**0.73, 0.008**	**0.01, 0.01**
Pulse rate x # Bunches/pulse	f_{rep} [Hz] x N_{bunch}	5 x 1312	700
Beamstrahlung Parameter	χ_{av} , χ_{max}	0.06, 0.15	969, 1721
Beam Power	P [MW]	**2.6**	**0.12**
Luminosity	L [$cm^{-2}s^{-1}$]	**3E+33**	**3E+33**

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

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

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

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

reaching fully non-perturbative regime

Radiation Probability

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

$$\boldsymbol{W < 1}$$

acceptable radiation loss

Disruption Parameter

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

$$\boldsymbol{D < 0.01}$$

small disruption

NpQED Collider scale

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

On the Prospect of Studying Nonperturbative QED with Beam-Beam Collisions

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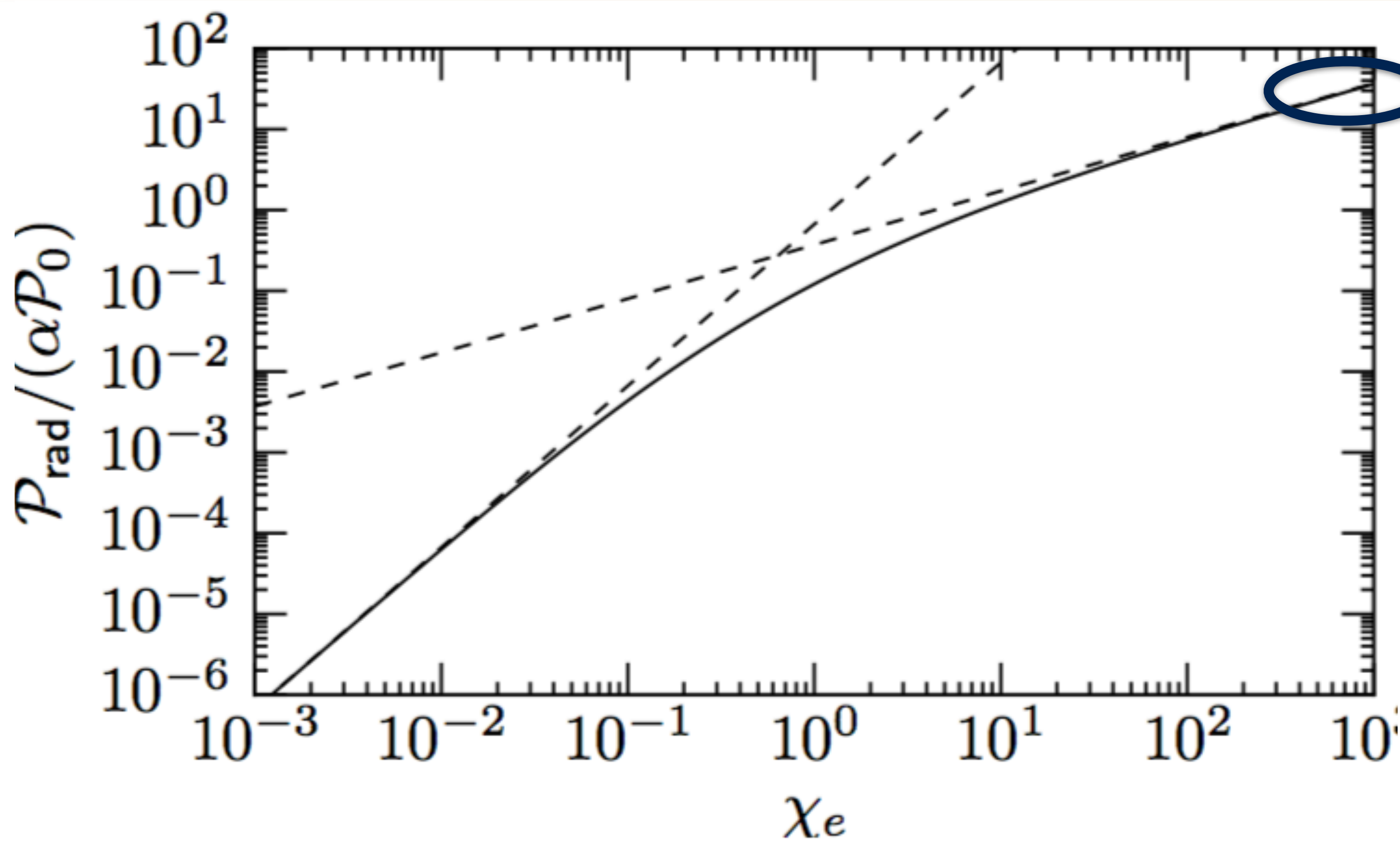
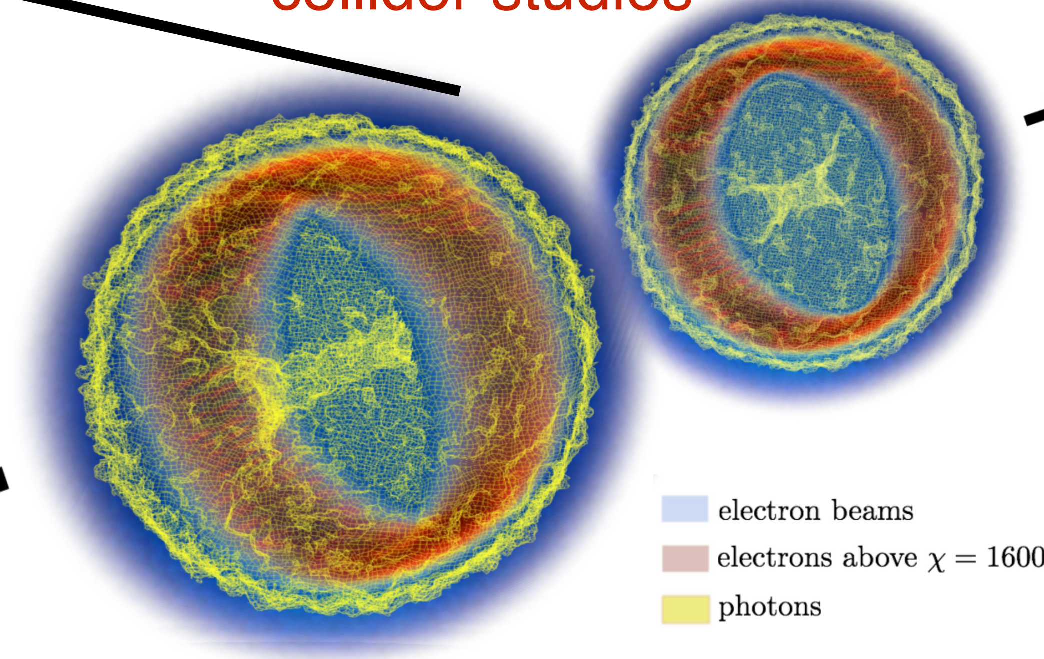
[5]National Research Nuclear University MEPhI, Moscow, Russia
(Dated: July 10, 2018)

We demonstrate the possibility of probing for the first time the fully nonperturbative regime of quantum electrodynamics. By using tightly compressed and focused electron beams in a 100 GeV-class particle collider, beamstrahlung radiation losses can be mitigated, allowing the particles to experience extreme electromagnetic fields. Three-dimensional particle-in-cell simulations confirm the viability of this approach. The experimental forefront envisaged has the potential to establish a novel research field and to stimulate the development of a new theoretical methodology for this yet unexplored regime of strong-field quantum electrodynamics.

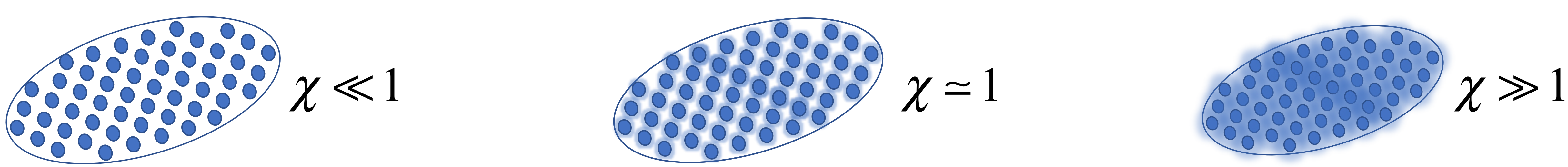
Different Scales of Strong Field: *Non-perturbative QED*



Future ~100GeV collider studies



Fully Non-perturbative QED: induced mass of photon exceeds mass of electron due to strong external field (expansion parameter $\alpha\chi^{2/3} > 1$)



Experimentally approach regime where existing theory breaks down

Conclusion:

Ultrashort intense electron bunches can enable new science:

- Gamma ray source through filamentation
  - requires 10% predicted FACET-II beam intensity
- Beamstrahlung suppression (allows for >10x reduction in ILC beam power)
  - At 100 GeV ~100 nm (~5x shorter bunches compared to FACET-II beams)
- Virtual particles dominated collisions (Non-perturbative QED)
  - 140pC, 10x10x10 nm^3 beams (modified ILC final focus)