Extreme Electron Bunch Compression

GARD ABP Workshop #1, LBNL
December 10, 2019

Glen White,
SLAC

U.S. DEPARTMENT OF ENERGY
Office of Science

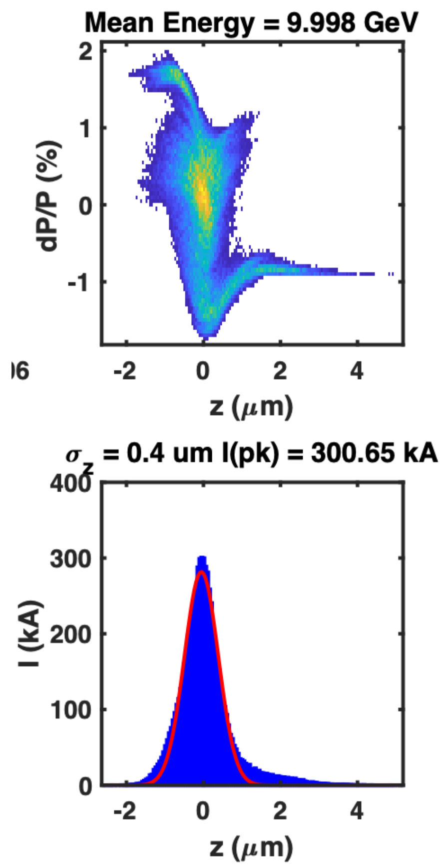
SLAC NATIONAL ACCELERATOR LABORATORY

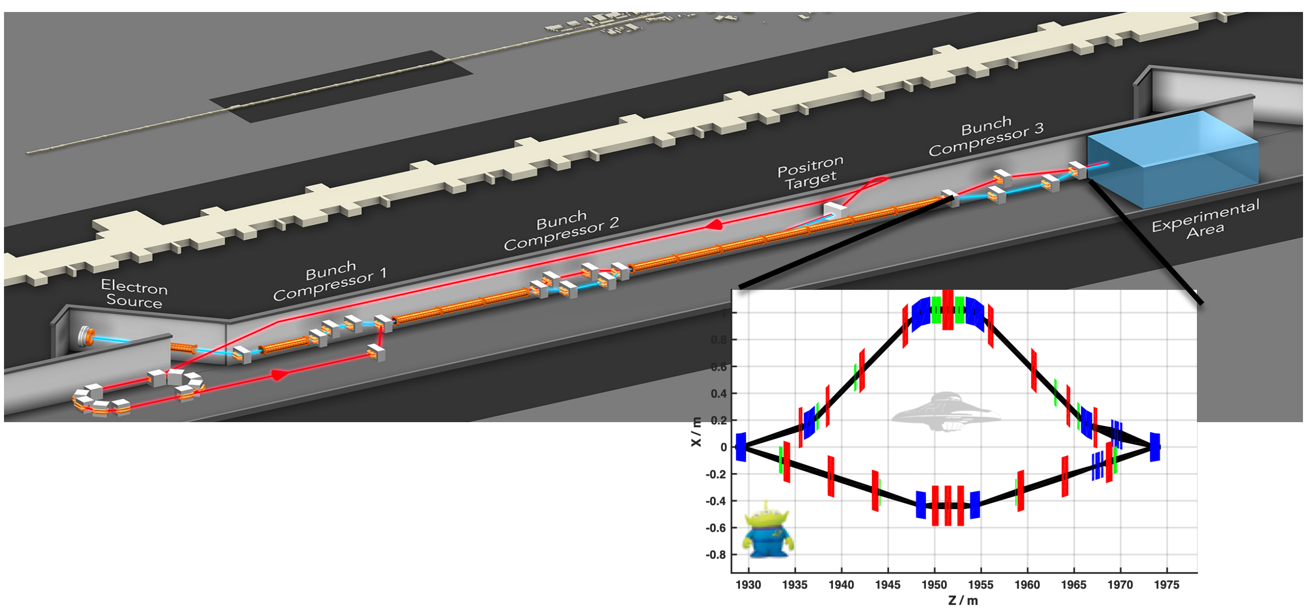
FACET-II Beam will Access New Regimes

Low-emittance (state of the art photoinjector) and ultra-short (improved compression) beam with re-designed final bunch compressor will generate:

- >300 kA peak current (~0.4 μm long)
- 2um -> ~100 nm focus by plasma ion column
- **$\sim 10^{12}$ V/cm** radial electric field
- **$\sim 10^{24}$ cm^{-3}** beam density

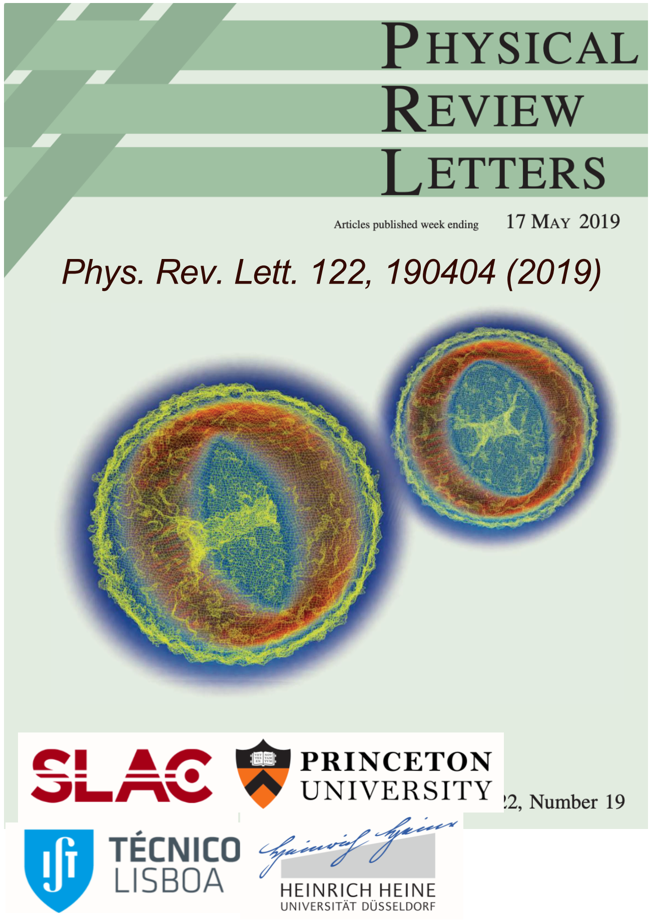
Proposals to further compress to I_{pk} > MA with CSR/wakes





Overview – Research Idea

- **What is the limit of electron bunch compression and what can highly compressed (σ_z < μm, I_{pk} >Mega-Ampere) electron beams be used for?**
- HEP: Controlling bunch length allows us to consider 2 novel regimes:
  - σ_z~100nm, Q~1nC: high beamstrahlung emission, high lumi for alternate LC gamma-gamma collider configuration
  - σ_z~10nm, Q~0.1nC: high beamstrahlung parameter, low radiation probability

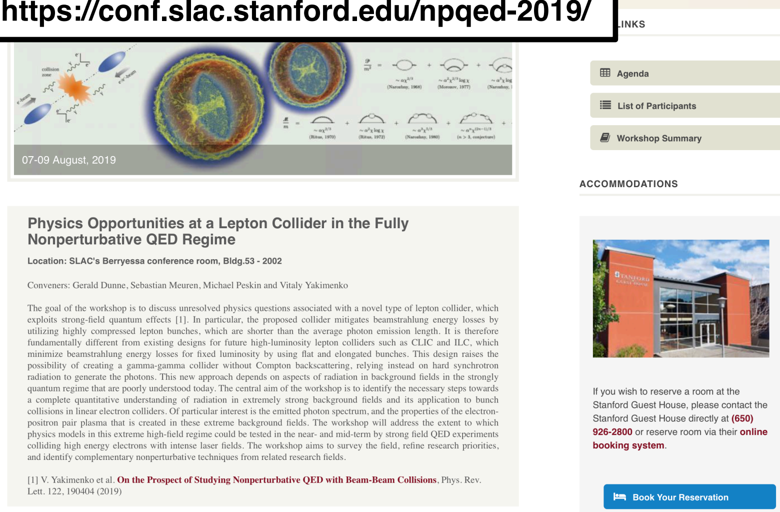


$$n_\gamma \propto \left(\frac{\sigma_z}{\gamma}\right)^{1/3} \left(\frac{N}{\sigma_x + \sigma_y}\right)^{2/3} \qquad \mathcal{L} = \frac{P_b}{E_b} \frac{N}{4\pi\sigma_x\sigma_y}$$

HEP Mission: Opportunities Enabled by Novel Regime of Colliding Lepton Beams in the Presence of Extreme Fields

SLAC

https://conf.slac.stanford.edu/npqed-2019/


07-09 August, 2019

LINKS

Agenda

List of Participants

Workshop Summary

ACCOMMODATIONS

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

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

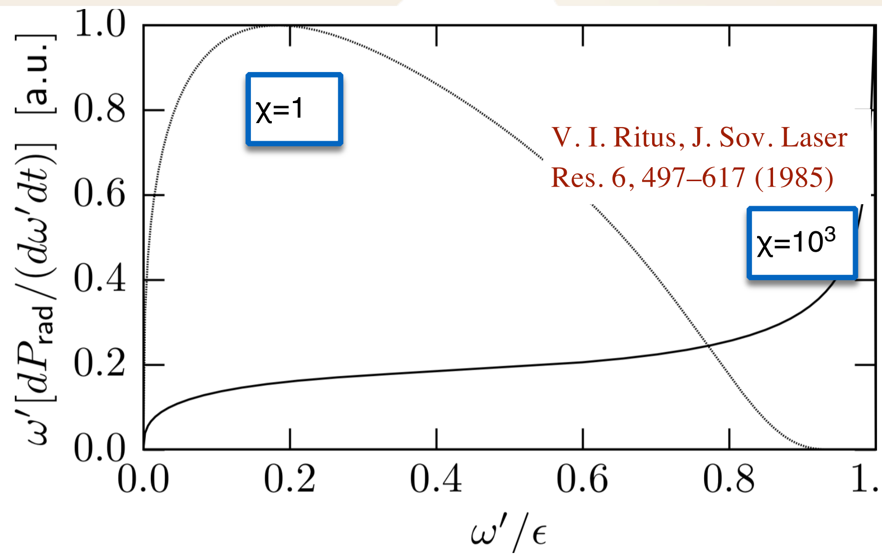
Conveners: Gerald Dunne, Sebastian Meuren, Michael Peskin and Vitaly Yakimenko

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 tested in the near- and mid-term by strong field QED experiments colliding high energy electrons with intense laser fields. The workshop aims to survey the field, refine research priorities, and identify complementary nonperturbative techniques from related research fields.

[1] V. Yakimenko et al. **On the Prospect of Studying Nonperturbative QED with Beam-Beam Collisions**, Phys. Rev. Lett. 122, 190404 (2019)

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.

Book Your Reservation



- **Laser-less γ-γ collider:** Determine which particle physics questions could be studied with such collider and at which energy scale. (ex. probe s-channel Higgs resonances, approach for future multiple-TeV scale collider etc.)
- **Fully non-perturbative QED physics:** need to develop framework for ***$\alpha\chi^{2/3} \gtrsim 1$*** *and explore what are its potentially observable features*
  - **Physics of e^-e^+ pair plasma** that is created in these extreme background fields and its effects on the colliding beams

Critical Field $E_{cr} \approx 10^{16}$ V/cm

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

Linear Collider Luminosity Optimization

Parameter	Symbol [Unit]	ILC (TDR)	Collider with short bunches
Center mass Energy	E_{CM} [GeV]	250 GeV	
Beam Energy	E [GeV]	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
Geometric Luminosity	L [$cm^{-2}s^{-1}$]	3E+33	

HEP LC with round bunches: ~10 times reduction of required beam power

Accelerator R&D topics

SLAC

Source (5-10X LCLS-II):

- Improvement in transverse emittance ~0.3 -> 0.03 μm-rad (@ 100pC) depending on FFS requirements
- Preserved longitudinal emittances
- Limits to 6D brightness in damping rings rings?

Beam Dynamics/Compression: (5x FACET-II)

- Equivalent of strong transverse focusing for longitudinal beam dynamics
- CSR compensation
- Emittance preservation, jitter control

RF power sources and accelerator structures

- Improved phase stability

Beam delivery and control (accelerator design for automated control):

- Novel diagnostics and Machine Learning

Final Focus and Stability (similar *to CLIC with round, short beams)***:**

- High energy bandwidth FFS design useful

Beneficiaries/Synergies:

- **HEP:** Linear colliders, **BES:** LCLS-HE, DRLS, **NNSA:** MaRIE, **NP:** Electron-Ion colliders

Objectives

1. **Develop use case(s) for >MA scale electron beams (low Q, high Q)**
   - Attosecond FEL physics
   - HEP: Collider (e- e-, round beams)
     - γγ @ 125GeV using beamstrahlung: s-channel Higgs production (alternative to LC gamma-gamma concept)
     - γγ @ >TeV (discovery machine, low-power c.f. conventional LC designs?)
   - SFQED, instability physics, gamma ray sources etc
   - Others: Lithography?? Low-Q UED type applications?
2. **Construct "zeroth-order" design for MA compression & beam collision to demonstrate feasibility of technology -> *2020 White Paper***
   - Low-jitter, emittance preserving Linac + BC
     - "passive chirp" : CSR wiggler, laser, plasma
   - High energy final compressor + FFS
3. **Design test facility for demonstrating compression technologies (FACET-III)**
   - Study max I_{pk} vs. final E
   - Cost effective machine to build which demonstrates tech and provides useful physics

Workshop Questions (1)

- **Desirable outcome?**
  - Push FACET-II as hard as possible, learn how to perform beam diagnostics, develop simulation tools
  - Use tools in-hand and developed as a result of FACET-II experience to design MA-scale accelerator
  - Understand use cases
    - npQED, gamma-gamma collider, low-beamstrahlung collider, FEL, …
- **Impacts**
  - Modified electron collider design, expanded physics reach, options for v. high energy
- **Fits into GARD ABP missions:**
  - Speaks to all ABP “Grand Challenges”
  - Enables future HE colliders by addressing beamstrahlung issues
  - Enables higher lumi, reducing required collider beam power and costs
  - Enables multiple physics programs at FACET-II, a GARD operational facility
    - Including training of accelerator physics

Workshop Questions (2)

SLAC

- **How can it fail, what can go wrong? Is it testable?**
- Highly non-linear compression + focusing optics
  - Critical components are modular and testable
- CSR emittance-growth compensation
  - Have multiple tools to study, continuing debate about completeness of CSR modeling
  - FACET-II perfect testing ground
  - Also common ground with larger FEL community wanting to push peak power, energy reach – collaborations exist
- After established modeling tools: use start-to-end tracking to understand stability challenges, CSR compensation
  - Issues like μbunching hard to study (especially for high Q)
- Experimental measurement/validation a key concern
  - Leverage ML expertise

ABP Grand Challenges (1)

#1: (peak) Beam Intensity frontier

- FACET-II already pushing beyond state-of-the-art in I_{pk} (>100kA @ Q>1nC)
  - **2020-2025 timescale**
- Developing tools to diagnose and simulate FACET-II will allow exploration of compression limits

#2: Beam Quality

- Enhanced Final Focus System: highly achromatic focusing optics (ILC/CLIC) + analogous emittance preserving longitudinal focusing system
  - This is a key design challenge to be addressed on similar timescale to above

ABP Grand Challenges (2)

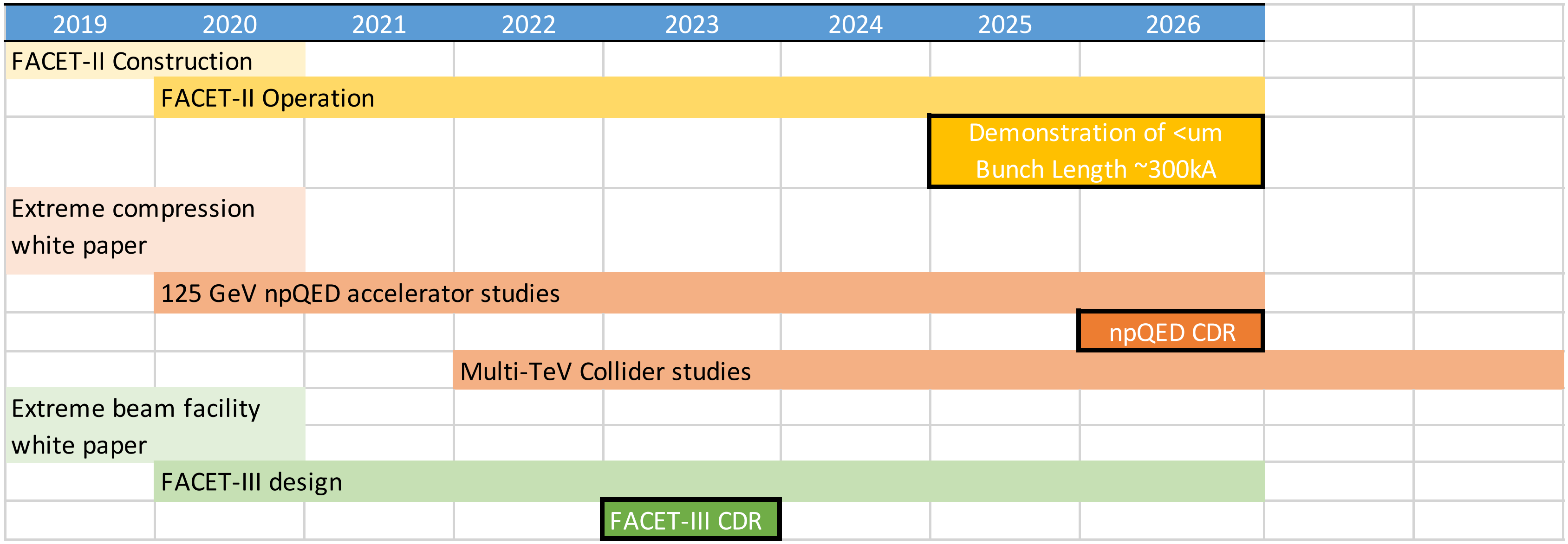
#3: Beam Control

- 100X improvement in Lumi at colliders (per bunch crossing at similar charge) achieved by going to round-beam collisions with v. short bunches (suppressing beamstrahlung)
- Control of particle distributions in longitudinal phase-space demonstrated by manipulating & controlling CSR

#4: Beam Prediction

- Verification of source-IP tracking, including space-charge, wakefields, ISR, CSR etc @ FACET-II
- Pursue ML interface for FACET-II
  - Online longitudinal phase-space prediction
    - Train with model & TCAV images
    - Deploy for longitudinal diagnostics with operational PWFA & extend below TCAV resolution limit

Roadmap & Current Activity



- **Collaboration on understanding & mitigation of CSR**
  - **SLAC, LBNL, Stony Brook, BNL, UCLA, U Texas, NIU**
- **Collaboration on understanding beam-beam physics (npQED) in extreme field regime**
  - **SLAC, Princeton, Harvard, Penn, Heidelberg, Dusseldorf, Jena, Lisbon …**
- **Study of applications for FEL's (attosecond science)**
  - **SLAC, UCLA**
- **Accelerator design (FACET-II,FACET-III, npQED Collider)**
  - **SLAC, UCLA**

Backup Slides…

Beamstrahlung Optimization @ High Lumi

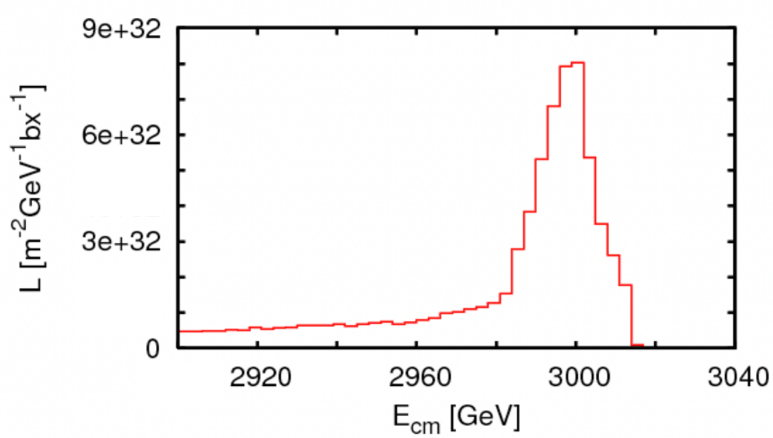
SLAC

- Small intense e+/e- bunches required for high luminosity
- Large field of opposite bunch results in strong acceleration producing synchrotron radiation ("beamstrahlung")
- The stochastic nature of the photon emission process in the quantum regime broadens the energy distribution of colliding beams.

$$n_\gamma \propto \left(\frac{\sigma_z}{\gamma}\right)^{1/3} \left(\frac{N}{\sigma_x + \sigma_y}\right)^{2/3} \qquad \mathcal{L} = \frac{P_b}{E_b} \frac{N}{4\pi\sigma_x\sigma_y}$$

$$\sigma_x \gg \sigma_y \qquad R = \frac{\sigma_x}{\sigma_y} \qquad \mathcal{L} \propto \frac{n_\gamma^{2/3}}{\sqrt{\sigma_z}\sigma_y} \frac{R+1}{R}$$

CLIC luminosity spectrum



Existing LC designs aim to keep beamstrahlung small with flat (R>>1) beams to minimize both backgrounds and energy spread induced in collisions

HEP Mission: 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:

Phys. Rev. Lett. 122, 190404 (2019)

Quantum Parameter

$$\chi_{av} \approx \frac{5}{12}\frac{N\alpha\lambda\!\!\!^-_c{}^2}{\sigma_r\sigma_z^*}$$

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

reaching fully non-perturbative regime

Radiation Probability

$$W \approx \alpha\chi_{av}^{2/3}\frac{\sigma_z^*}{\lambda\!\!\!^-_c}$$

$W < 1$

acceptable radiation loss

Disruption Parameter

$$D \approx \frac{2N\alpha\lambda\!\!\!^-_c\sigma_z^*}{\sigma_r^2}$$

$D < 0.01$

small disruption

NpQED Collider scale

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

SLAC · PRINCETON UNIVERSITY · TÉCNICO LISBOA · MEPhI · HEINRICH HEINE UNIVERSITÄT DÜSSELDORF

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

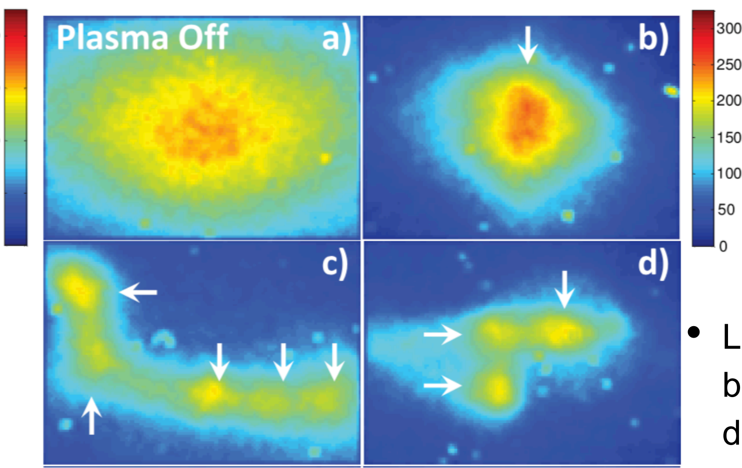
PIs: S. Corde (Ecole Polytecnique), F. Fiuza (SLAC), K. Marsh (UCLA)

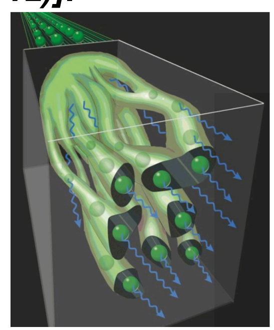
SLAC

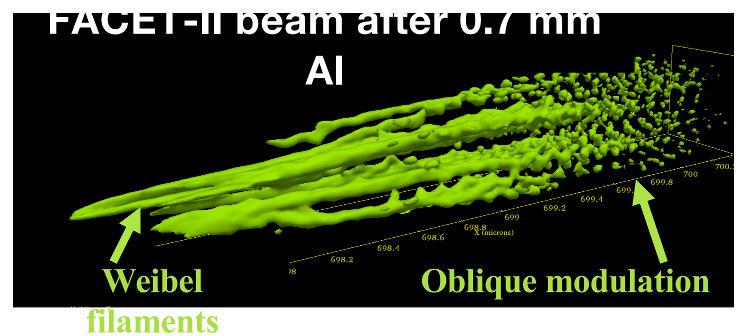
Gamma-ray source of unprecedented efficiency and brightness based on synchrotron radiation from beam electrons in extreme magnetic fields of its filaments developed due to the instability

- 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.

Hierarchy of Numbers that Enables NpQED Collider

SLAC

- Formation Length for hard photon (for 100GeV e- in $\chi >> 1$ field): $L_f \sim 1 nm$
- Field switching length: $\sigma_z \sim 10\ nm$
- Length to emit a hard photon with probability ~1 : $L_f / \alpha \sim 100 nm$

This hierarchy ensures:

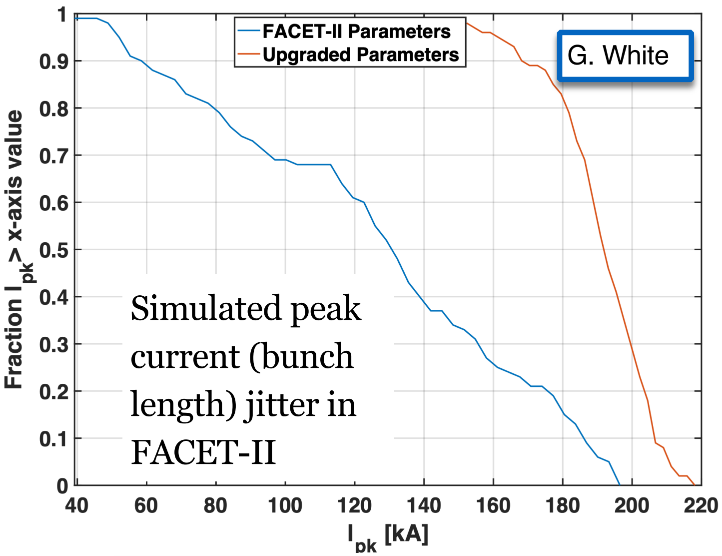
- Majority of electrons go through the collision without emitting hard photons and preserving initial energy as a result ($\sigma_z << L_f / \alpha$)
- Local Constant Field Approximations is valid ($L_f << \sigma_z$)

For 100 GeV:

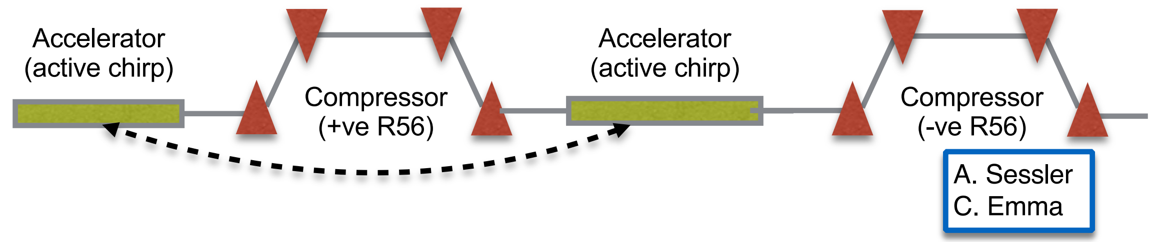
$$\chi_{max} = \frac{\gamma E_r}{E_{cr}} \sim \underbrace{\gamma\alpha}_{\sim 1400} \underbrace{\frac{N_e \lambda_c^2}{\sigma_z \sigma_r}}_{\sim 1}$$

Working Group to Study Challenges Associated with “Extreme” Compression: Stability of the Compression

SLAC



Compensation of phase jitter impact on bunch length:

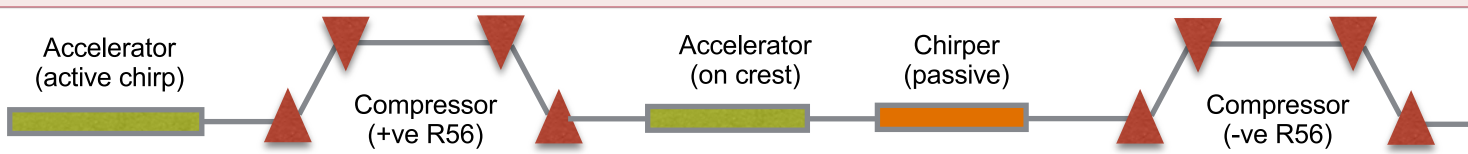


$$\frac{\Delta\sigma_z}{\sigma_z} = [C_1^2 E_1/E_2 - 1/C_2]\frac{\Delta\phi_1}{\phi_1} + [C_1 C_2 E_1/E_2 - 1/C_1]\frac{\Delta\phi_2}{\phi_2} => C_2 = \frac{E_2}{C_1^2 E_1}$$

Two stage jitter compensation ex.: C1~3, C2~3, E1~300MeV, E2~10GeV

Numbers are not practical for XFEL-linacs; likely useful for 100GeV scale machine.

Nonlinear terms will be important



Approaches to improved stability:

- Alternating sign and multi-stage compensation (equivalent to FODO focusing concept)
- High-Q RF (SRF) and resonant enhancement laser cavities for improved phase stability
- Passive chirpers: self induced wakes (longer bunch => smaller induced chirp)

Compensating Effect of the Coherent Synchrotron Radiation (CSR) in Bunch Compressors

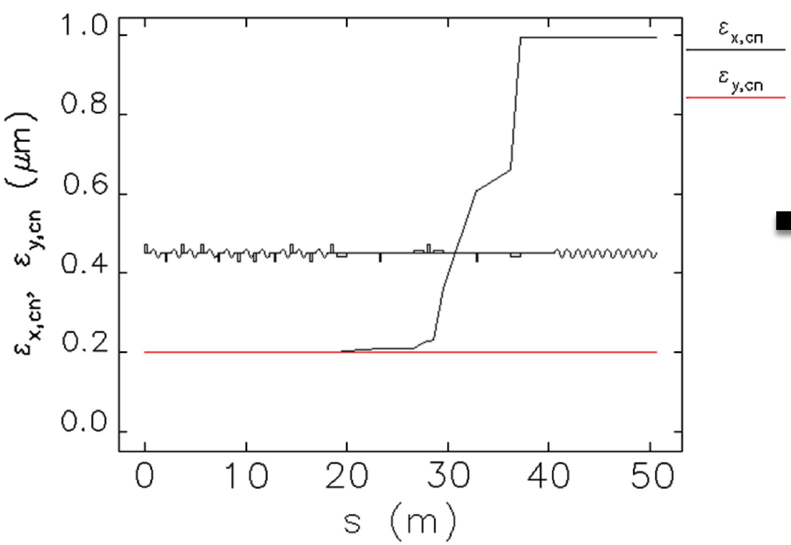
SLAC

- CSR is a key contributor in emittance degradation for short intense bunches
  - longitudinal energy variation induced by CSR wake is coupled to the transverse plane through nonzero local dispersions in the chicane

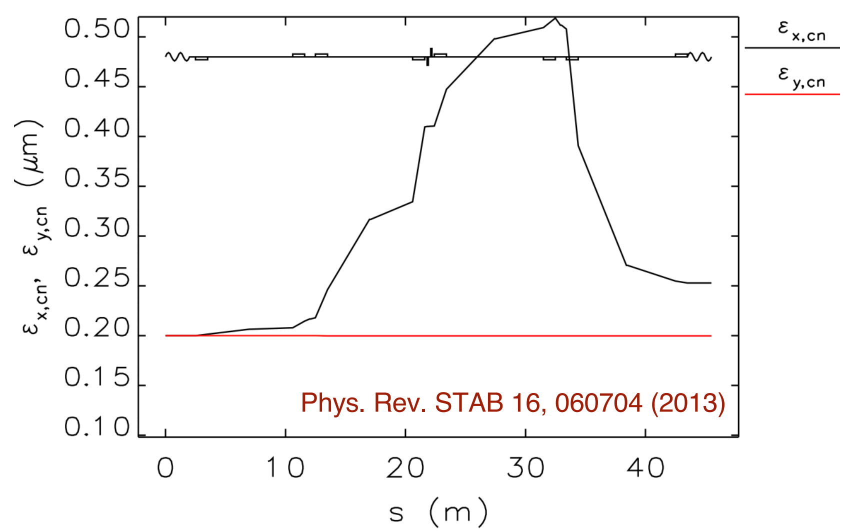
D. Douglas, JLAB-TN-98-012, 1998

- Longitudinal and transverse degrees of freedom can be decoupled and detrimental effects of CSR can be mostly suppressed by using opposite sign dispersion with reversing bending directions

Emittance blowup due to CSR with single chicane



Emittance growth compensated with two chicanes



Cancelation of CSR kicks with optics balance were simulated and tested for 10kA beams.

3D CSR theory and experiments are needed for NpQED class beams

Strong Field QED in Laboratory Experiments

- *Critical Field* $E_{cr} \approx 10^{16}$ *V/cm Critical Intensity* $I_{cr} \approx 4.6 \times 10^{29}$ *W/cm*^{2}
- *Decisive Measure: electric field in the particle rest frame (E*):*

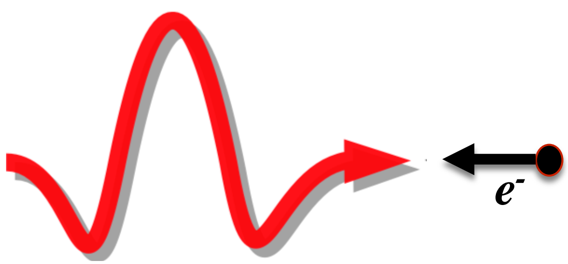
$$\chi = \frac{\sqrt{pF^2p}}{E_{cr}mc^2} = \frac{\varepsilon}{mc^2}\frac{E}{E_{cr}} = \frac{E^*}{E_{cr}}$$

A. Di Piazza, et. al Extremely high-intensity laser interactions with fundamental quantum systems. Rev. Mod. Phys. 84, 1177 (2012)

V. N. Biaer et al, Interaction of high-energy electrons and photons with crystals. Sov. Phys. Usp. 32 972 (1989)

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

Electron-laser interaction

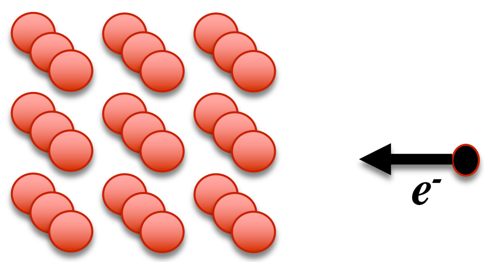


Quantum parameter

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

ε: electron energy, I: Laser intensity

Particle-crystals interaction

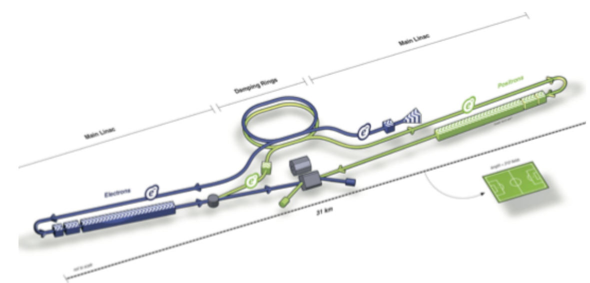


Quantum effects threshold

$$\chi \approx \frac{\varepsilon}{mc^2}\frac{U_0}{mc^2}\frac{r_e}{\alpha a_s}$$

U_0: transverse potential, a_s: screening distance

Beam-beam interaction



Beamstrahlung parameter

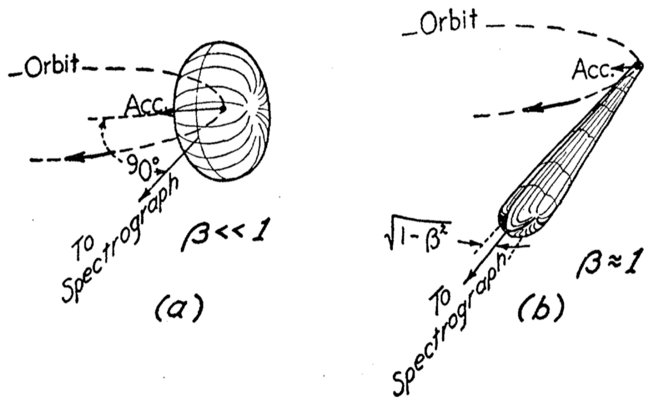
$$\chi \approx 0.57 \frac{\varepsilon}{mc^2}\frac{2Nr_e^2}{\alpha\sigma_z(\sigma_x + \sigma_y)}$$

N: Number of particles, $\sigma_{x,y,z}$: dimensions of the bunch

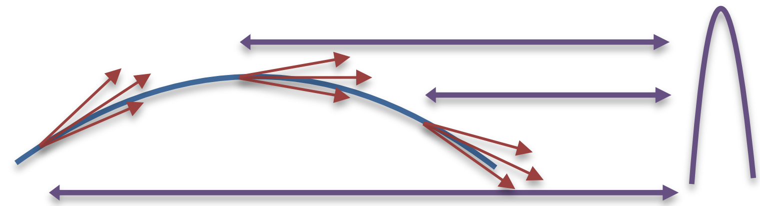
Synchrotron radiation: classical pattern, spectrum, power

SLAC

e^- with energy ε: circular orbit, radius



D. H. Tomboulian and P. L. Hartman, Phys. Rev. 102, 1423 (1956)



Angular divergence: $\theta = 1/\gamma$

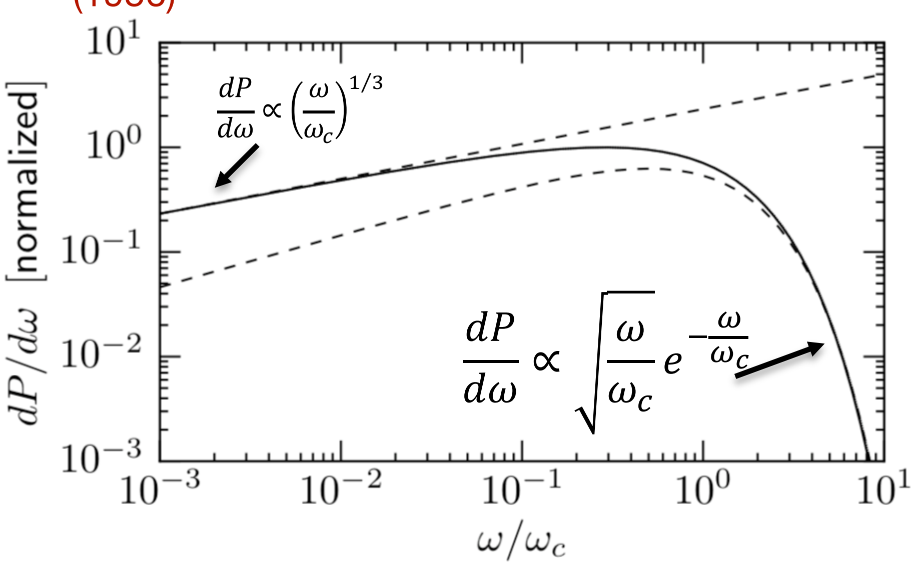
Formation length: $l_f = \rho/\gamma$

(contributing circular segment)

Burst duration: $T = (1/v - 1/c)$

Critical frequency: $\omega_c \sim 1/T = c\gamma^3/\rho$

(typical frequency, Fourier transform)



Photon emission probability per formation time c/l_f is α;

typical energy of the radiated photon: $\hbar\omega_c$

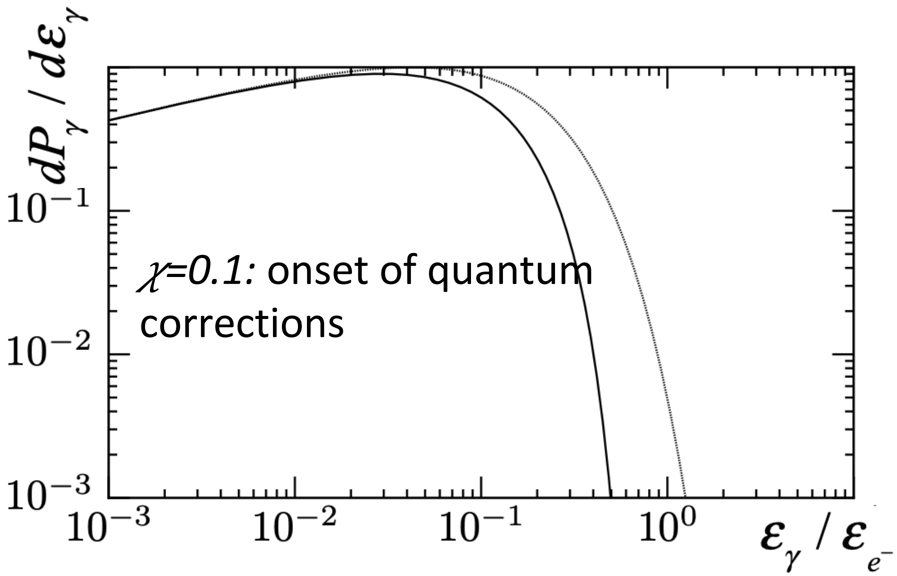
Total radiation power emitted per electron: $P \sim \alpha c/l_f \cdot \hbar\omega_c$

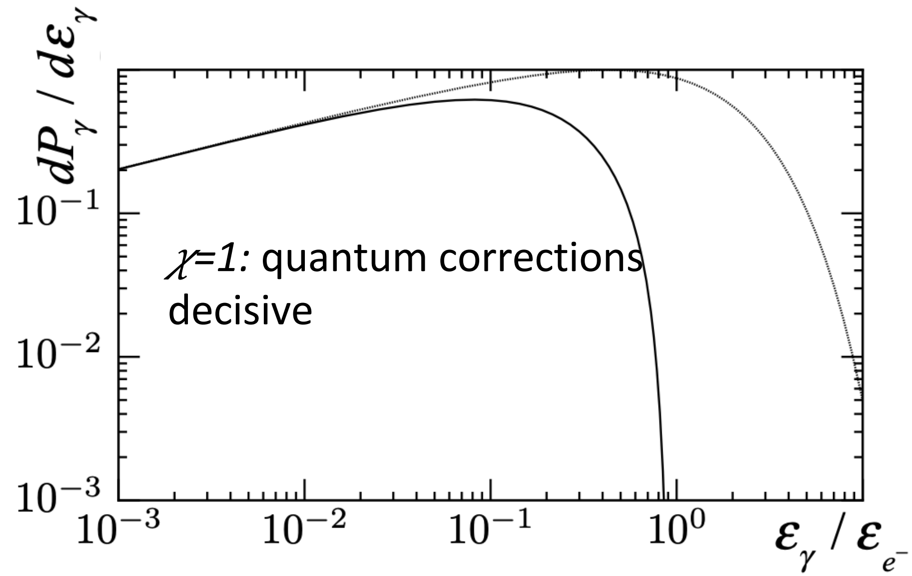
Classical and Quantum regimes

χ << 1: ***classical regime:*** *Quantum effects are small, pair production is exponentially suppressed*

$\chi \gtrsim 0.1$, χ <~10: ***transition to quantum regime:*** *Recoil and pair production are important*

Comparison between the classical (dotted curves), and the quantum (solid curves)





Formation length: $l_f = \chi^{1/3}\, l_{f\_classical}$

Baier, Katkov, Strakhovenko: Electromagnetic Processes at High Energies in Oriented Single Crystals (1998)

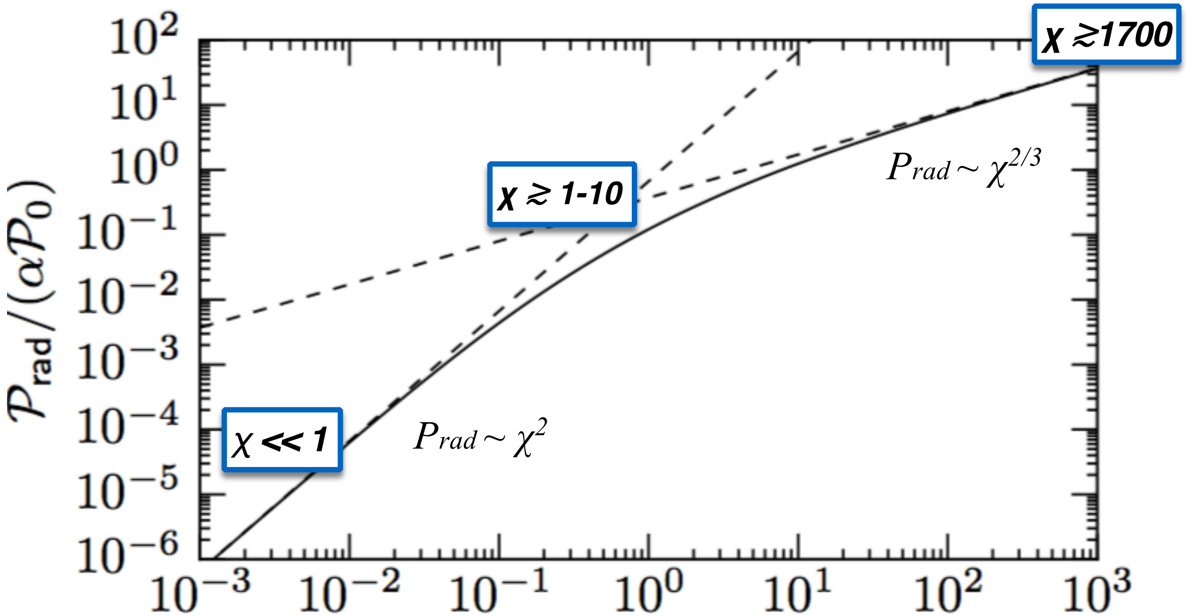
Different Scales of Strong-Field QED

$\chi << 1$: ***classical regime:*** *Quantum effects are small, pair production is exponentially suppressed*

$\chi \gtrsim 0.1$, $\chi <\sim 10$: ***transition to quantum regime:*** *Recoil and pair production are important*

$\chi \gtrsim 10$, $\alpha\chi^{2/3} < 1$: ***quantum regime:*** *Importance of pair production cascades, the radiation field is a perturbation*

$\alpha\chi^{2/3} \gtrsim 1$ ($\chi \gtrsim 1700$): ***fully non-perturbative regime:*** *Perturbative treatment of the radiation field breaks down*



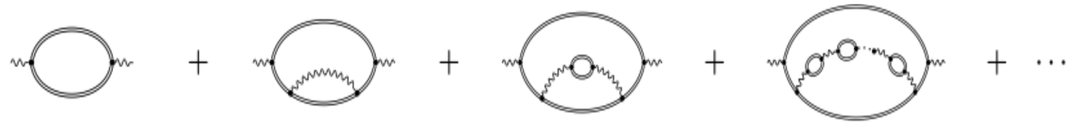
Developing framework for non-perturbative regime was generally considered to be of minor academic interest for quantum electrodynamics because of the inaccessibly large field scale at which the breakdown occurs

Fully Non-Perturbative QED

Scaling of diagrams considered so far

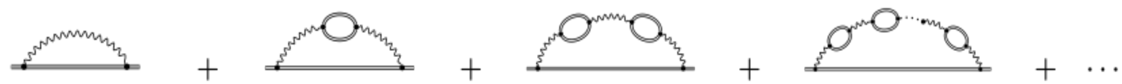
V. I. Ritus, Ann. Phys. 69, 555–582 (1972)
N. B. Narozhny, Phys. Rev. D 21, 1176–1183 (1980);
A. M. Fedotov, J. Phys.: Conf. Ser. 826, 012027 (2017);

$\frac{\mathcal{P}}{m^2} =$



$\sim \alpha\chi^{2/3}$ (Narozhny, 1968); $\sim \alpha^2\chi^{2/3}\log\chi$ (Morozov, 1977); $\sim \alpha^3\chi\log^2\chi$ (Narozhny, 1980); $\sim \alpha^n\chi^{(2n-3)/3}$ ($n > 3$, conjecture)

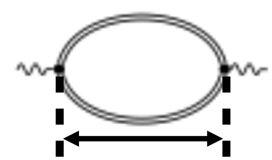
$\frac{\mathcal{M}}{m} =$



$\sim \alpha\chi^{2/3}$ (Ritus, 1970); $\sim \alpha^2\chi\log\chi$ (Ritus, 1972); $\sim \alpha^3\chi^{5/3}$ (Narozhny, 1980); $\sim \alpha^n\chi^{(2n-1)/3}$ ($n > 3$, conjecture)

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)*



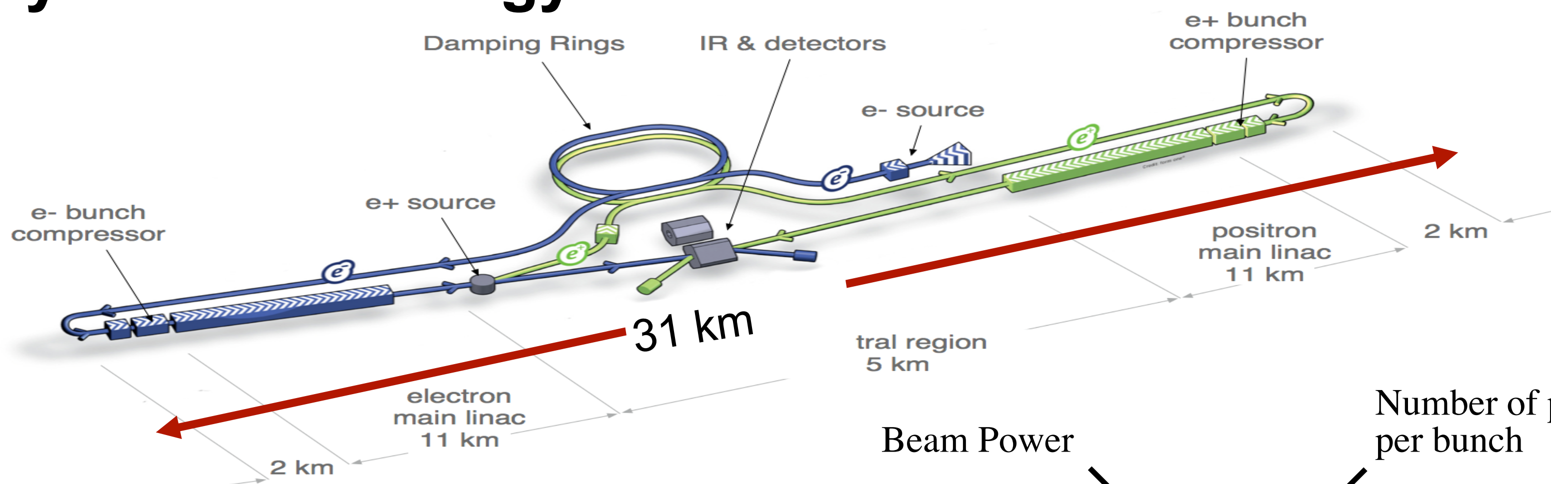
The resulting field-induced mass scale $M \sim m\chi^{1/3}$ **independent of** m (note, $\chi \sim m^{-1/3}$),

$m_\gamma(\chi) = \alpha\chi^{2/3} m$: ***breakdown of perturbation theory when*** $\alpha\chi^{2/3} \gtrsim 1$ ***or*** $m_\gamma(\chi) > m$

250-500 GeV range Linear Collider likely candidate for next large accelerator in particle physics - "hesitations" are due to costs

ILC can be stretched to 1 TeV, CLIC to 3 TeV – new technologies needed to go much higher energies

Today's LC technology



The Luminosity Challenge:

Beam Power

Number of particles per bunch

$$\mathcal{L} = \frac{P_b}{E_b} \frac{N}{4\pi\sigma_x\sigma_y}$$

Beam Energy

Area of the beam

In all cases luminosities at least around ~10^{34}-10^{35} cm^{-2} s^{-1} are needed