小型化自由电子雷射
compact FEL

自由电子雷射冬季课程

2019年01月17日10:00-11:00

VLASOV-MAXWELL EQUATIONS

- Vlasov-Maxwell equation

$$\begin{cases} \left(\dfrac{\partial}{\partial \tau} + \dfrac{\partial}{\partial \theta} + \dfrac{1}{2ik_s k_w}\nabla_\perp^2\right)E = \dfrac{D_1}{\gamma_0}\int F d\gamma \\ \dfrac{\partial F}{\partial \tau} + 2i\dfrac{\gamma - \gamma_0}{\gamma_0}F = \dfrac{D_2}{\gamma_0}\dfrac{\partial f_0}{\partial \gamma}E \end{cases}$$

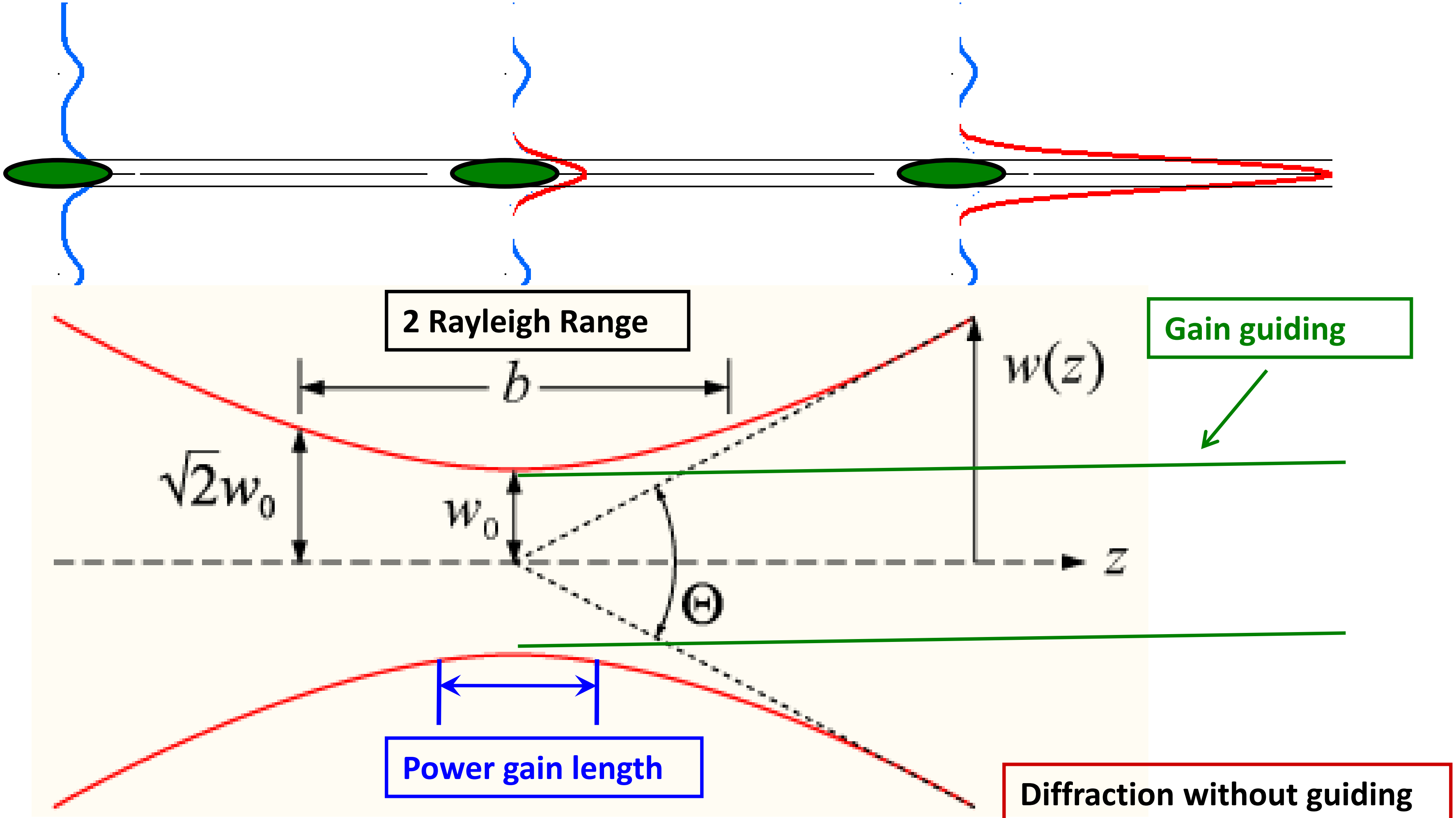
- Notations

$$D_1 = \frac{e a_w n_0 [JJ]}{2\sqrt{2} k_w \varepsilon_0} \text{ and } D_2 = \frac{e a_w [JJ]}{\sqrt{2} k_w m c^2}$$

$$(2\rho)^3 = (2D_1 D_2)/\gamma_0^3$$

MOORE'S GUIDED MODE

- Gain guiding and Rayleigh range



- Gain should balance diffraction

POWER GAIN LENGTH

- Physical requirement
  - Scaled beam size $$\tilde{a}^2 \equiv 2\rho a^2$$
  - Physical meaning

$$\tilde{a}^2 \equiv 2\rho a^2 = 2\rho 2k_s k_w r_0^2$$

$$= \frac{4}{\sqrt{3}} \frac{4\sqrt{3}\pi\rho}{\lambda_w} \frac{\pi r_0^2}{\lambda_s} \sim \frac{L_R}{L_G}$$

  - The ratio between the Rayleigh range with e-beam size waist and the power gain length

RULE OF THUMB

- Different cases:
  - If $\tilde{a} >> 1$, then $L_R >> L_G$. Diffraction loss is compensated by gain, system is dominated by gain → we have 1-D limit: diffraction negligible, but many modes are degenerate
  - If $\tilde{a} << 1$, then $L_R << L_G$. Diffraction is significant, we have 3-D effect. Gain is less than 1-D. But higher mode grow much slower, a single mode dominates. Beam size becomes constant — optical guiding.
  - If $2 < \tilde{a} < 6$. Growth rate ~ 1-D, single mode, optical guiding, transverse coherent for long undulator, and very high gain.

ELECTRON BEAM QUALITY

- 3-D effect: diffraction
  - We compare L_G with L_R
- Energy spread
  - Explain why it should be smaller than ρ
- Angular spread

$$\varepsilon << \frac{\pi}{k_\beta L_G k_s} \Rightarrow \varepsilon_n << \frac{\pi\gamma}{k_\beta L_G k_s}$$

  - LCLS case: L_G=5 m; k_β=1/7.3 m^{-1}; k_s=2π/(1.5E-10) m^{-1}; γ=28100 → ε_n<< 3 mm – mrad (LCLS design: 1.2 mm-mrad)
  - The conventional criteria of $\varepsilon<\lambda_s/(4\pi)$--not that good at all!

$$\varepsilon << \frac{\lambda_s}{4\pi} \Rightarrow \varepsilon_n << \frac{\lambda_s \gamma}{4\pi} \approx 0.3 \text{ mm - mrad}$$

FREE ELECTRON LASER

- FEL Electron Beam Requirements

$$\boxed{\varepsilon_N << \frac{\lambda_s \gamma}{2(L_G / \beta)}}$$

radiation wavelength

(~1.5 μm realistic goal)

Transverse emittance: ε_N < 1 μm at 1.5 Å, 15 GeV

peak current

undulator period

$$\boxed{\sigma_\delta < \rho \approx \frac{1}{4}\left(\frac{1}{2\pi^2}\frac{I_{pk}}{I_A}\frac{\lambda_u^2}{\beta\varepsilon_N}\left(\frac{K}{\gamma}\right)^2\right)^{1/3}}$$

Energy spread:

<0.08% at I_{pk} = 4 kA,
$K \approx 4$, $\lambda_u \approx 3$ cm, …

beta function

undulator 'field'

$$\boxed{L_g \approx \frac{\lambda_u}{4\pi\sqrt{3}\rho}}$$

FEL gain length:

$20L_g$ > 100 m for $\varepsilon_N \approx 1.5$ μm

- Need to increase peak current, preserve emittance, maintain small energy spread, and provide stable operation

COHERENT EMISSION: REVISITED

Electromagnetic radiation emitted by charged particles is an indispensable part of majority of course on general electrodynamics. Even as of today, fundamental questions are still being asked and research results are published on top journal.

PHYSICAL REVIEW LETTERS **121,** 010402 (2018)

Quantum Limitation to the Coherent Emission of Accelerated Charges

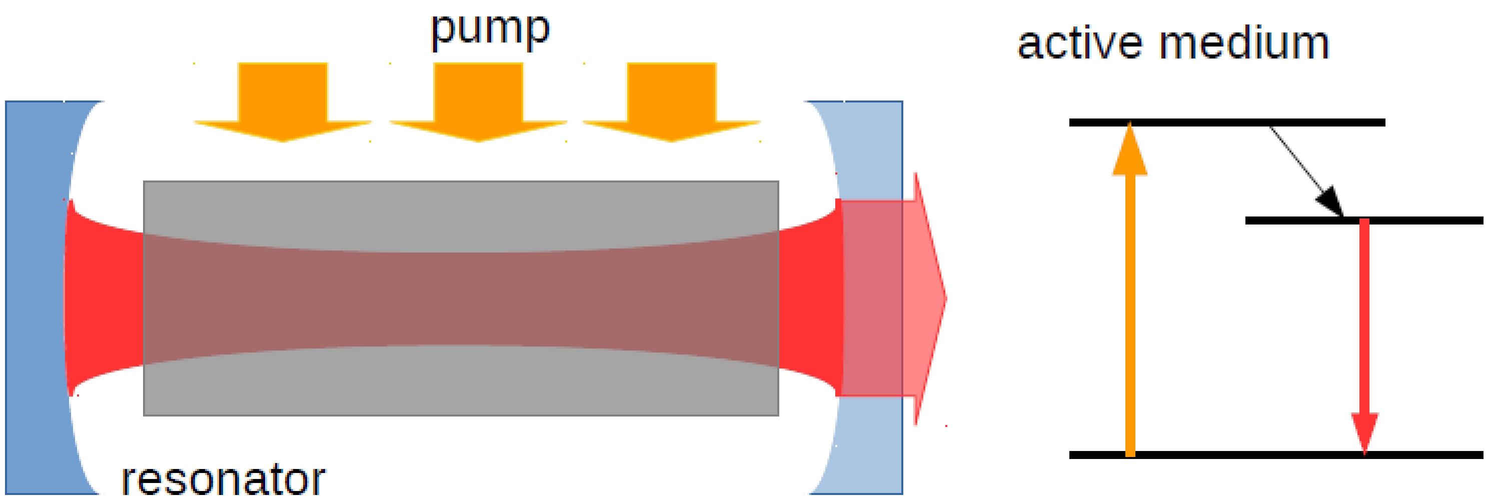
A. Angioi and A. Di Piazza*

Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

(Received 1 December 2017; revised manuscript received 24 April 2018; published 5 July 2018)

Accelerated charges emit electromagnetic radiation. According to classical electrodynamics, if the charges move along sufficiently close trajectories they emit coherently; i.e., their emitted energy scales quadratically with their number rather than linearly. By investigating the emission by a two-electron wave packet in the presence of an electromagnetic plane wave within strong-field QED, we show that quantum effects deteriorate the coherence predicted by classical electrodynamics even if the typical quantum nonlinearity parameter of the system is much smaller than unity. We explain this result by observing that coherence effects are also controlled by a new quantum parameter which relates the recoil undergone by the electron to the width of its wave packet in momentum space.

Conventional lasing scheme in x-ray region: lack of principal components



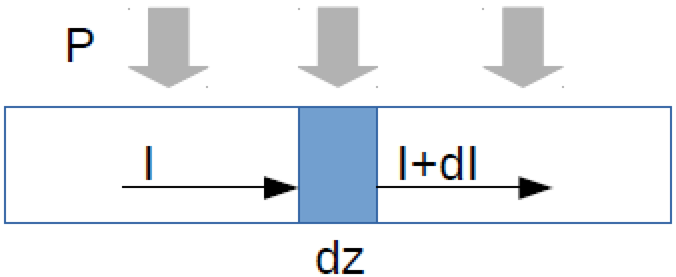
pump:	high powers needed: problematic
resonator:	crystal optics: problematic
active medium:	inner shell, short lived, ~ok

New ideas are needed

- X-ray free electron lasers
- Any other options?

Pumping power requirements for x-ray lasers

Intensity growth in inverted medium



$$\frac{\partial I(z)}{\partial z} = gI(z) + \frac{\Omega}{4\pi} n\Gamma_{sp}\hbar\omega$$

Gain *g* is given by:

$$g = \sigma(n_e - n_g) \simeq \frac{\Gamma_{sp}}{\Gamma_{tot}}(n_e - n_g)\lambda^2 \sim n_e\lambda^2$$

Pump needed to sustain population inversion:

$$P = n_e\Gamma_{sp}\hbar\omega \sim n_e\lambda^{-3}$$

Pumping power needed to maintain a specific gain:

$$P \propto g\lambda^{-5}$$

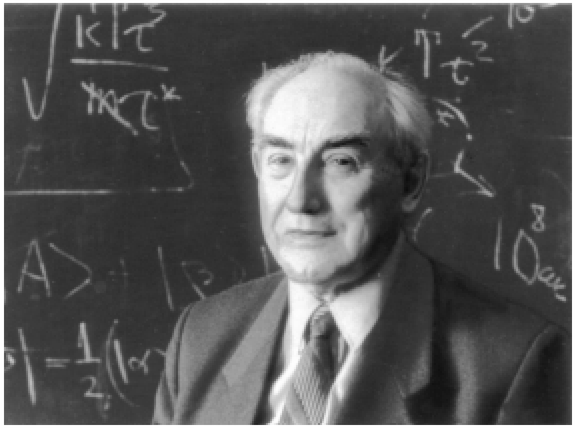
J. J. Rocca, Rev. Scient. Instr. **70**, 3799 (1999).

Motivation

X-ray lasers: a fundamental problem

V.L.Ginzburg, Nobel lecture '2003:

List of 30 problems of physics and astrophysics that are of special importance and interest:



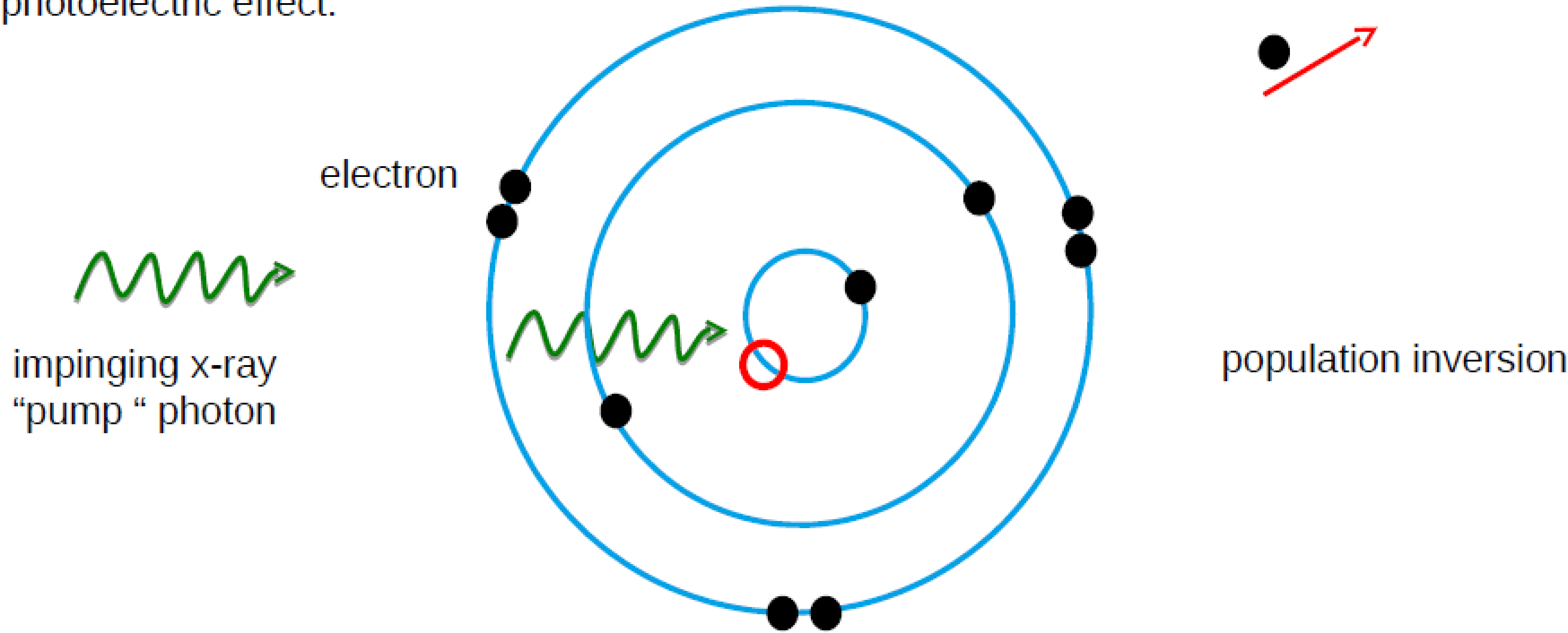
1. Controlled nuclear fusion.
2. High-temperature and room-temperature superconductivity (HTSC and RTSC).
3. Metallic hydrogen. Other exotic substances.
4. Two-dimensional electron liquid (anomalous Hall effect and other effects).
5. Some questions of solid-state physics (heterostructures in semiconductors, quantum wells and dots, metal – dielectric transitions, charge and spin density waves, mesoscopics).
6. Second-order and related phase transitions. Some examples of such transitions. Cooling (in particular, laser cooling) to superlow temperatures. Bose–Einstein condensation in gases.
7. Surface physics. Clusters.
8. Liquid crystals. Ferroelectrics. Ferrotoroics.
9. Fullerenes. Nanotubes.
10. The behavior of matter in superstrong magnetic fields.
11. Nonlinear physics. Turbulence. Solitons. Chaos. Strange attractors.
12. X-ray lasers, gamma-ray lasers, superhigh-power lasers.
13. Superheavy elements. Exotic nuclei.
14. Mass spectrum. Quarks and gluons. Quantum chromodynamics. Quark-gluon plasma.
15. Unified theory of weak and electromagnetic interactions. $W^{\pm}$ and Z^0-bosons. Leptons.
16. Standard model. Grand unification. Superunification. Proton deca… Neutrino mass. Magnetic monopoles.
17. Fundamental length. Particle interaction at high and superhigh energi… Colliders.
18. Nonconservation of CP-invariance.
19. Nonlinear phenomena in vacuum and in superstrong magnetic fiel… Phase transitions in a vacuum.
20. Strings. M-theory.
21. Experimental verification of the general theory of relativity.
22. Gravitational waves and their detection.
23. The cosmological problem. Inflation. Λ-term and 'quintessence'. Relationship between cosmology and high energy physics.
24. Neutron stars and pulsars. Supernova stars.
25. Black holes. Cosmic strings (?).
26. Quasars and galactic nuclei. Formation of galaxies.
27. The problem of dark matter (hidden mass) and its detection.
28. The origin of superhigh-energy cosmic rays.
29. Gamma-bursts. Hypernovae.
30. Neutrino physics and astronomy. Neutrino oscillations.

V.L.Ginzburg, Rev. Mod. Phys, **76**, 981-998 (2004)

Photoioniztion of inner shell

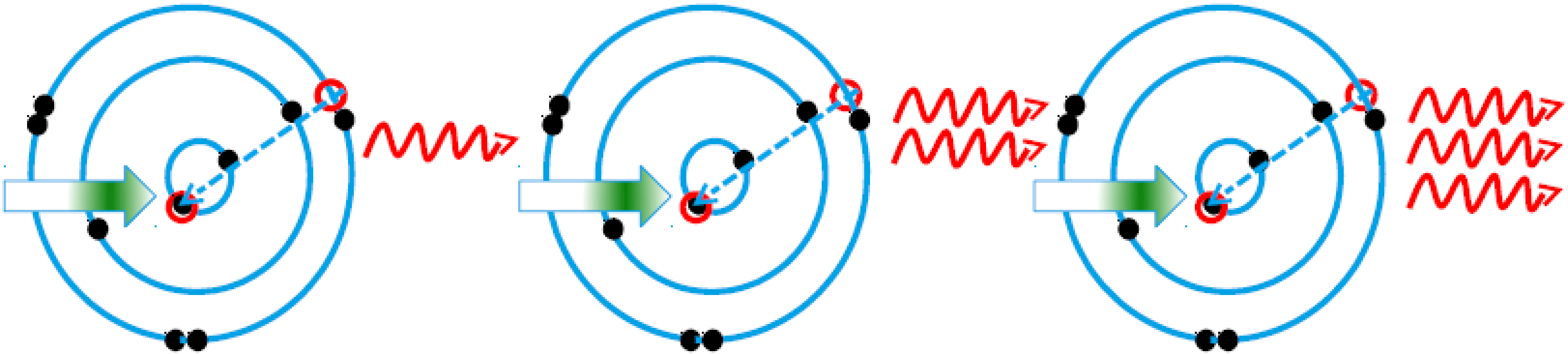
Ne atom

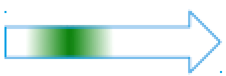
The photoelectric effect:



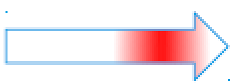
Atomic inner shell x-ray laser

Chain reaction of stimulated emission processes



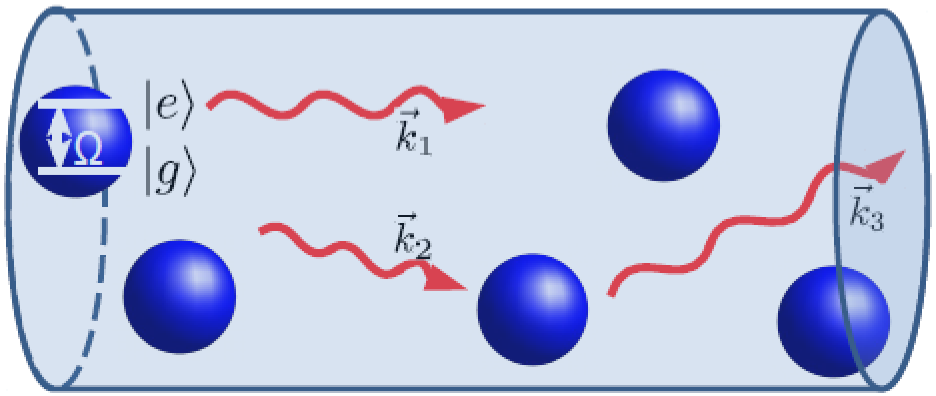


Absorption of the pumping XFEL beam



Amplification of the characteristic radiation, stimulated x-ray light

Light-matter interaction Hamiltonian



Matter (two-level atom) operators:

population inversion: $\hat{\sigma}_z = \frac{1}{2}(|e\rangle\langle e| - |g\rangle\langle g|)$

transitions (coherences): $\hat{\sigma}_+ = |e\rangle\langle g|, \hat{\sigma}_- = |g\rangle\langle e|$

Field operators:

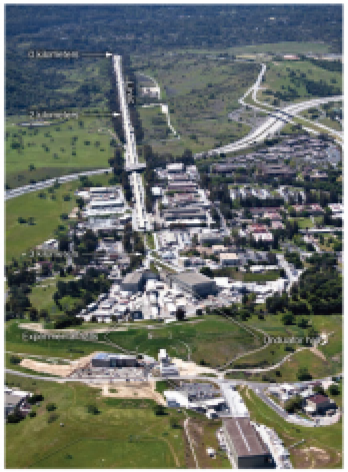
photon creation/annihilation: $\hat{a}^\dagger_{\vec{k},s}, \hat{a}_{\vec{k},s}$

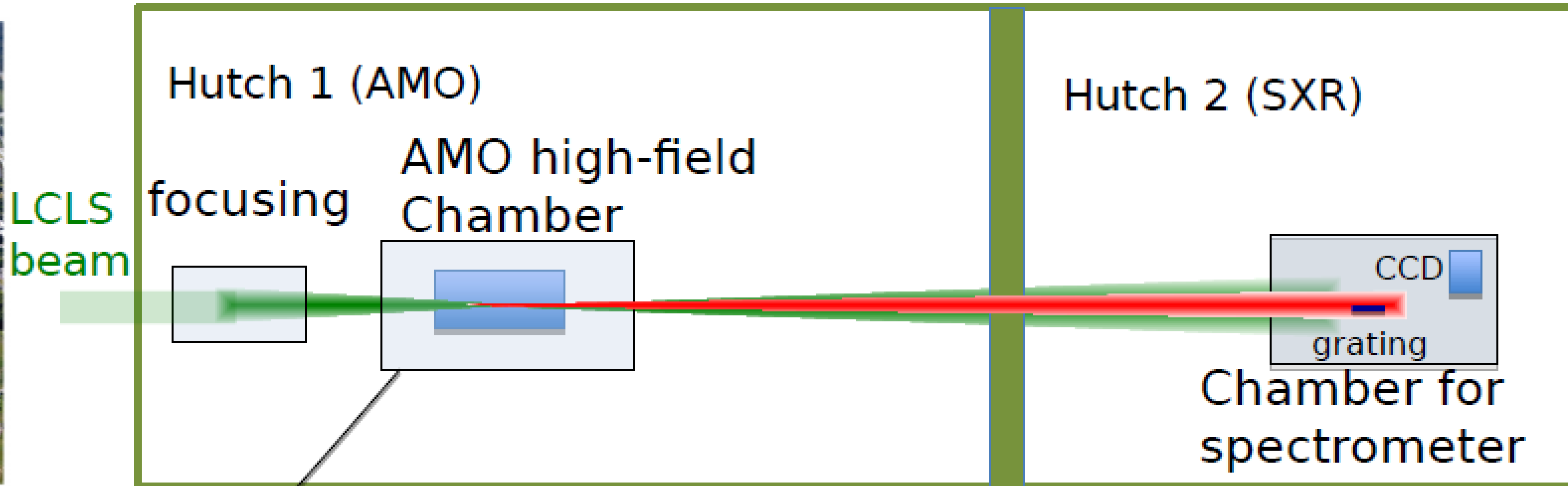
$$\hat{H} = \underbrace{\sum_a \hbar\Omega\hat{\sigma}_z^{(a)}}_{\text{atoms}} + \underbrace{\int d^3\vec{k} \sum_s \hbar\omega_{\vec{k}}\hat{a}^\dagger_{\vec{k},s}\hat{a}_{\vec{k},s}}_{\text{field}} + \underbrace{\int d^3\vec{k} \sum_{a,s} \hbar(g_{\vec{k},s}e^{i\vec{k}\vec{r}_a}\hat{\sigma}_+^{(a)}\hat{a}_{\vec{k},s} + g^*_{\vec{k},s}e^{-i\vec{k}\vec{r}_a}\hat{a}^\dagger_{\vec{k},s}\hat{\sigma}_-^{(a}}_{\text{atom-field interaction}}$$

Atom-filed coupling is proportional to dipole moment $g_{\vec{k},s} \sim \mu$

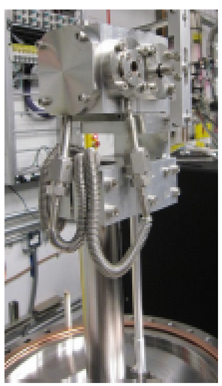
Experimental realization

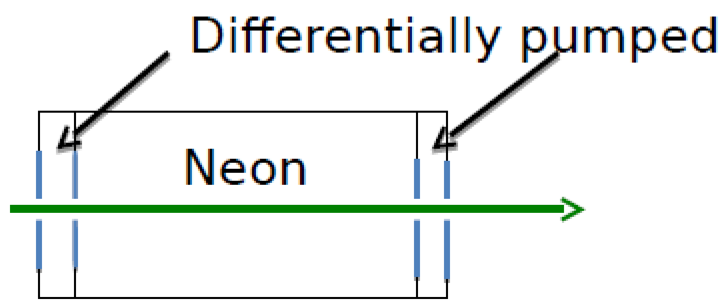
XFEL pump – atomic lasing in gas cell





Gas cell filled with neon (400-600 Torr)

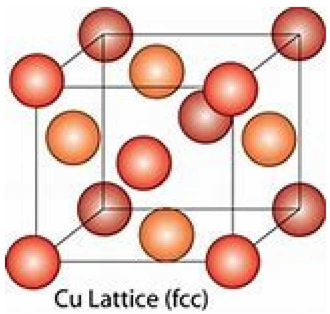


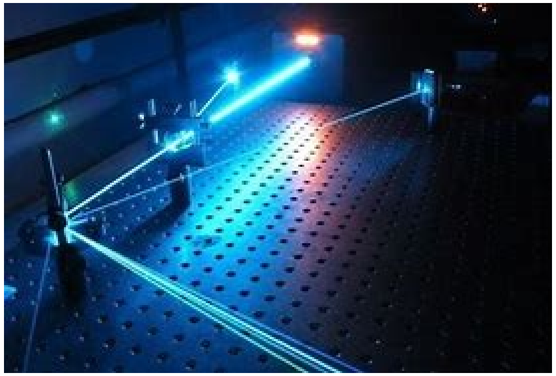


Rohringer et al., *Nature* **481**, 488 (2012)

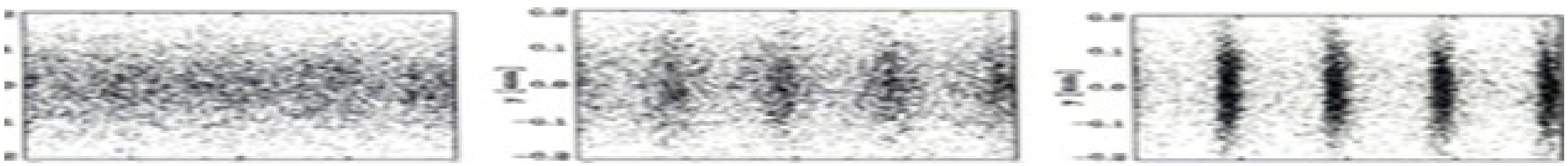
WHAT IS HAPPENING

- Laser on copper → electrons





- Electrons → coasting beam to microbunching



EMISSION

- Thermionic emission: 1000 K
- Photo-electric emission: 700 K
- Field emission: 1000 K

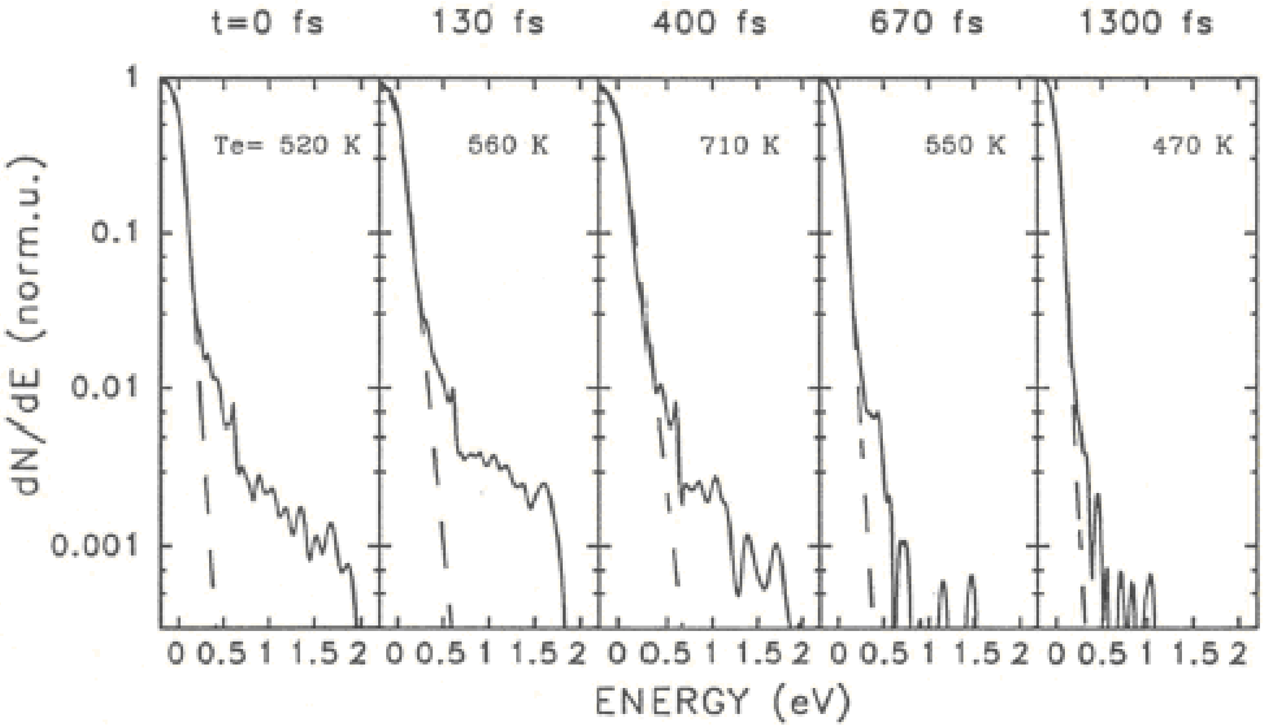


Fig. 1: Electron energy distribution function vs. energy with 120 μJ/cm^2 absorbed laser fluence at 5 time delays. The dashed line is the best Fermi-Dirac fit and the corresponding electron temperature, T_e, is shown. The vertical scale is in units of density of states.

OUTLINE

- Quantum Degeneracy
- Cold Atoms
- Cold Electrons
- Quantum Free Electron Laser

QUANTUM DEGENERACY

In the rest-frame of a beam of electrons propagating in the *z* direction, the dimensionless differential phase volume $d\Gamma$ is:

$$d\Gamma = \frac{1}{h^3} dx dp_x dy dp_y dz dp_z = \frac{dx d\beta_x dy d\beta_y dz d\beta_z}{(2\pi)^3 {\lambda\!\!\!^{-}_C}^3}$$

where $\beta_{x,y,z} = {}^{v_{x,y,z}}/_{c}$ and *c* is the speed of light, and $\lambda\!\!\!^{-}_C = {}^{\hbar}/_{m_e c} = 3.86 \times 10^{-13}$ m: electron Compton wavelength.

The total dimensionless phase volume Γ:

$$\Gamma = \frac{\varepsilon_x \varepsilon_y \varepsilon_z}{{\lambda\!\!\!^{-}_C}^3}$$

where

$$\varepsilon_x = \sqrt{(\langle x^2 \rangle - \langle x \rangle^2)\langle {\beta_x}^2 \rangle - \langle x\beta_x \rangle^2}$$: x-emittance

with similar definitions for ε_y and ε_z.

QUANTUM DEGENERACY

Let N_e be the actual number of electrons, and consider the ratio:

$$\delta_F = \frac{N_e}{\Gamma} = \lambda_C{}^3 \frac{N_e}{\varepsilon_x \varepsilon_y \varepsilon_z} = \lambda_C{}^3 B$$

where $B = {}^{N_e}/_{\varepsilon_x \varepsilon_y \varepsilon_z}$ is the "brightness".

The Pauli exclusion principle requires:

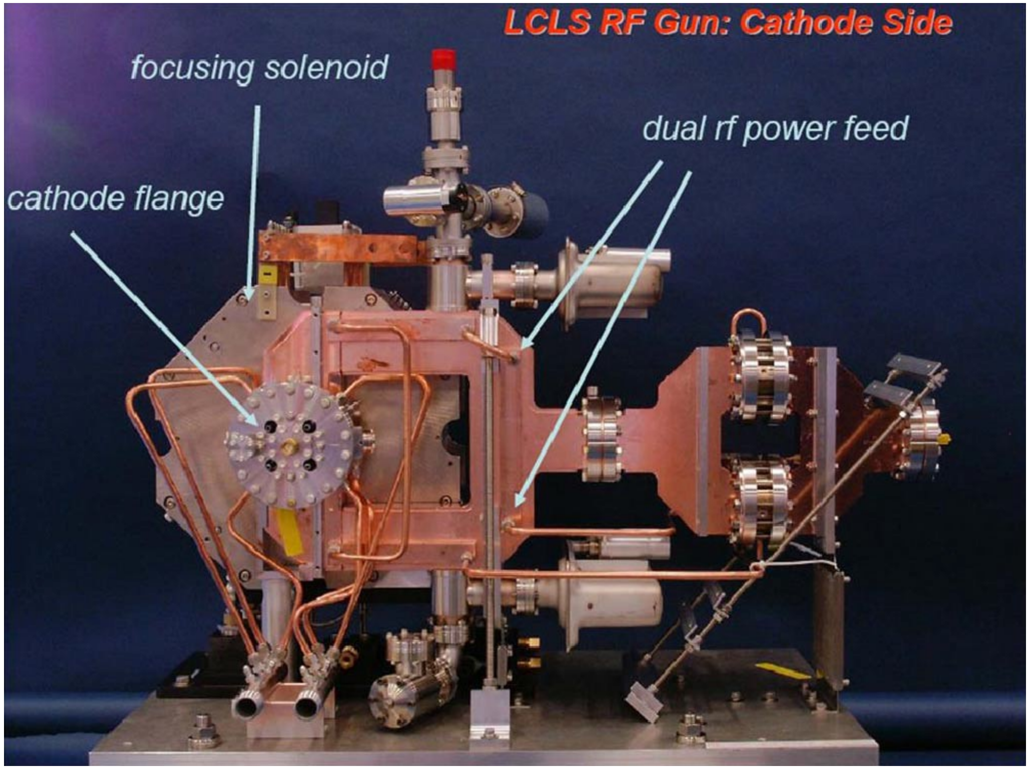
$$\delta_F \leq 1$$

for electrons of a given spin polarization; hence:

$$\varepsilon_x \varepsilon_y \varepsilon_z \geq \lambda_C{}^3$$

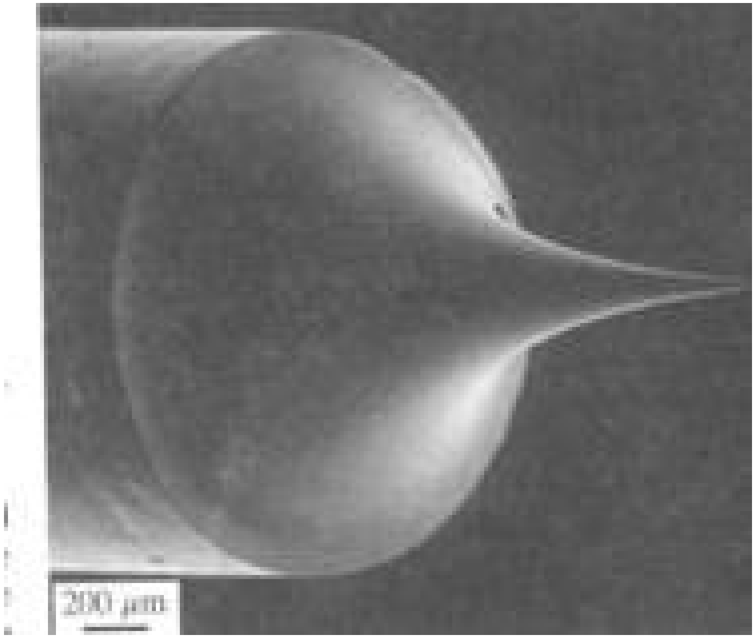
QUANTUM DEGENERACY

- In the case of low emittance RF photoinjectors for FEL and ERL applications (~ 1 nC, 10^{-6} m-rad emittance): $\delta_F \approx 10^{-11}$
  - Supercollider is colliding this kind of beam



QUANTUM DEGENERACY

- The highest brightness source presently in operation is a field emission source for electron microscope applications, where the tip is a carbon nanowire. For this source: $\delta_F \approx 10^{-5}$

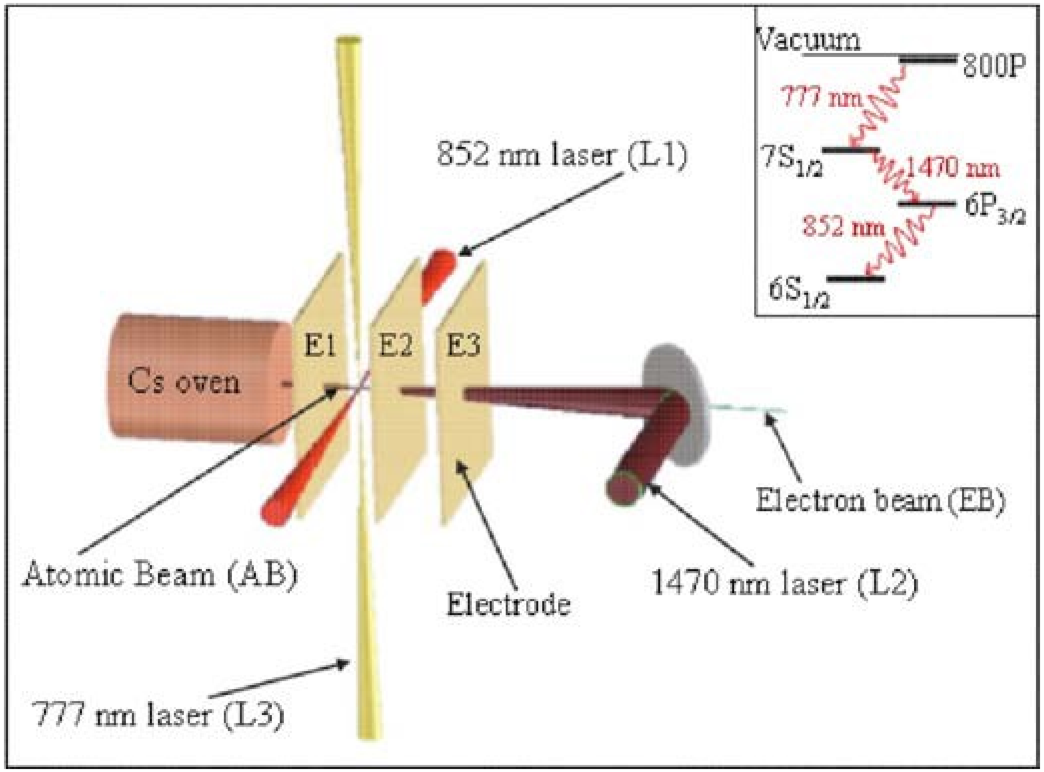


QUANTUM DEGENERACY

- Electrons inside a metal cathode before the extraction occupies almost all available states and thus have degeneracy parameter $\delta_F \sim 1$
- How do we loose all of that ?
  - Extraction mechanism: phonon scattering during extraction,…
  - Coulomb interaction: e^--e^- scattering after extraction

QUANTUM DEGENERACY

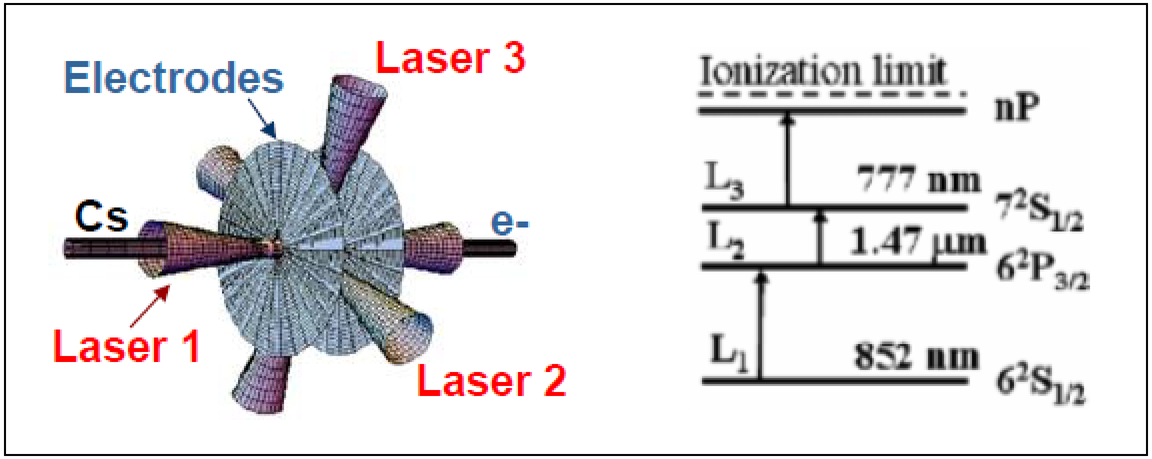
A quantum degenerate electron source



QUANTUM DEGENERACY

Eventually, we can get:

- $\varepsilon_{x,y} \cong 3.0\, \lambda\!\!\!^{-}_C$,
- $\varepsilon_z \cong 4.8\, \lambda\!\!\!^{-}_C$,
- and a fractional energy spread $\Delta E/E \approx 4 \times 10^{-5}$,
- $\delta_F \approx 2 \times 10^{-2}$



COLD ELECTRONS FROM COLD ATOMS

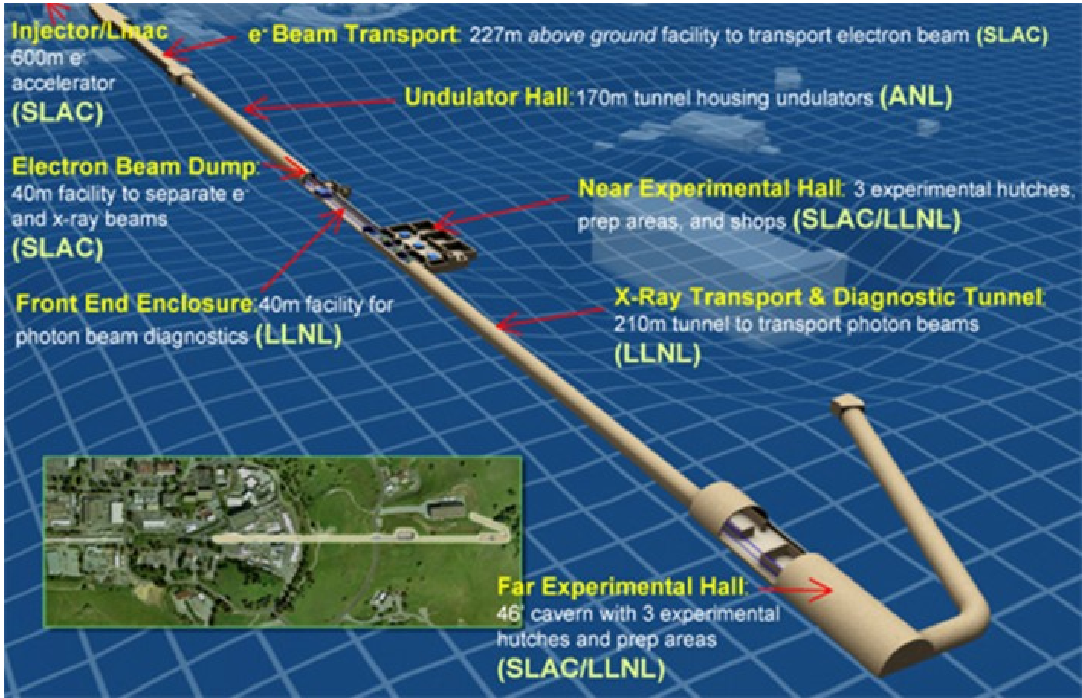
Ultracold electron sources based on near-threshold photoionization of laser-cooled atomic gases can produce ultrashort electron pulses with a brightness potentially exceeding conventional pulsed electron sources.

- At beam waist:
  - $\epsilon_{\perp,\mathrm{waist}} = \sigma_x \frac{kT}{mc^2}$, where σ_x the rms beam size and $T \equiv {}^{\langle {p_x}^2 \rangle}/_{(mk)}$ the effective electron temperature
  - $\epsilon_{\parallel,\mathrm{waist}} = \frac{1}{mc}\sigma_z \sigma_{p_z} = \frac{1}{mc}\sigma_t \sigma_{\mathrm{U}}$ with σ_t the rms bunch duration and the σ_{U} rms longitudinal energy spread

COLD ELECTRONS FROM COLD ATOMS

Conventional Pulsed RF: fully optimized normalized brightness (${}^{N}/_{{\epsilon_\perp}^2}$: the transverse phase space density cannot be improved any more) →$\epsilon_\perp \propto \sqrt{N}$

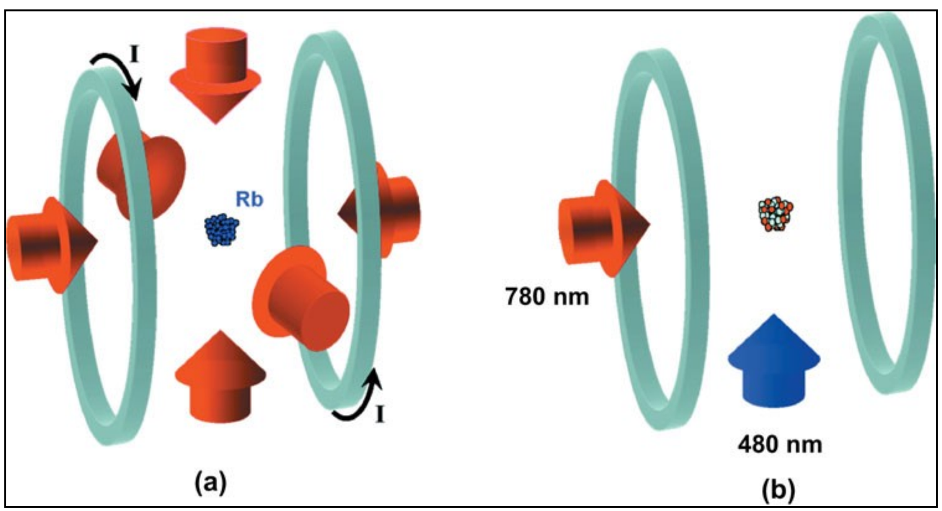
Cold Atoms: the electron and photon beams matched → $\frac{\epsilon_\perp}{\beta\gamma} \leq \frac{\lambda}{4\pi}$ →reduction of emittance allows lower beam energy → compact

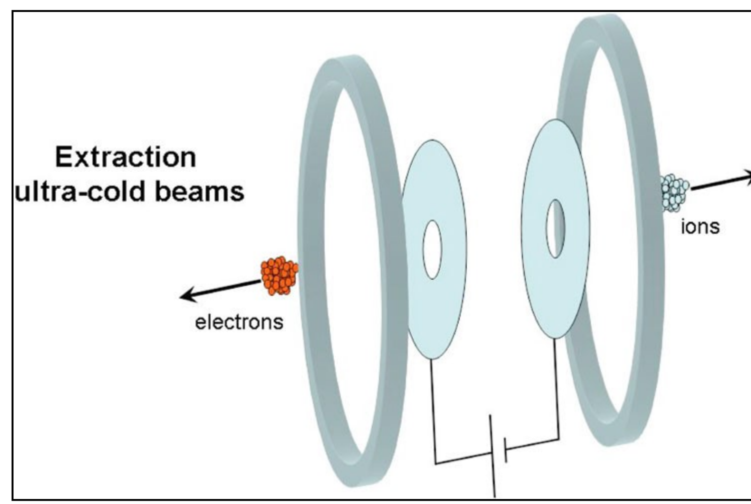


SET-UP

An ultra-cold atom cloud in a magneto-topical atom trap (MOT)

- Three orthogonal pairs of laser beams with a quadrupole magnetic field produced by two coils in anti-Helmholtz configuration
- The trapped gas is ionized just above threshold using a two-photon ionization scheme: for rubidium, 780 nm exciting atoms to the $5P_{3/2}$ state, a 480 nm ionizes the atom in $5P_{3/2}$ state





RYDBERG ATOMS

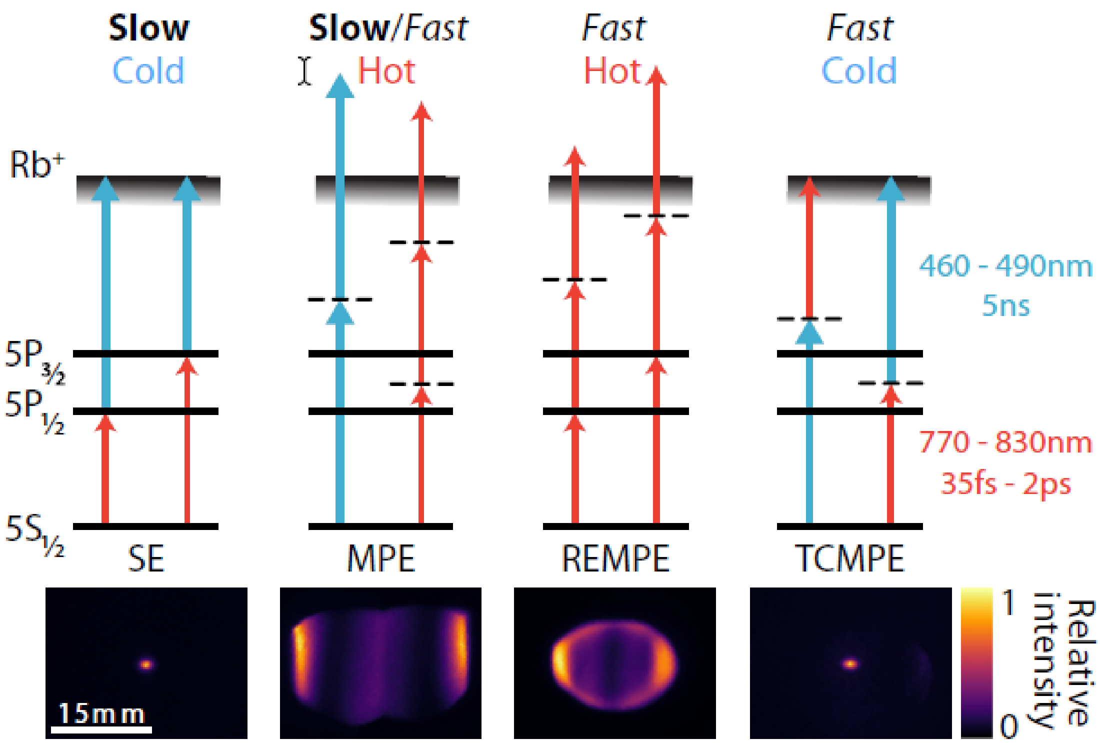


FIG. 2. Simultaneous illumination with two laser pulses can result in several excitation pathways: sequential excitation (SE), multiphoton excitation (MPE), resonance-enhanced multiphoton excitation (REMPE), and two-color multiphoton excitation (TCMPE). Only TCMPE produces electron bunches that are both cold and ultrashort. Virtual states are indicated as dashed lines. The false-color images show transverse momentum distributions of the detected bunches for the associated excitation pathways.

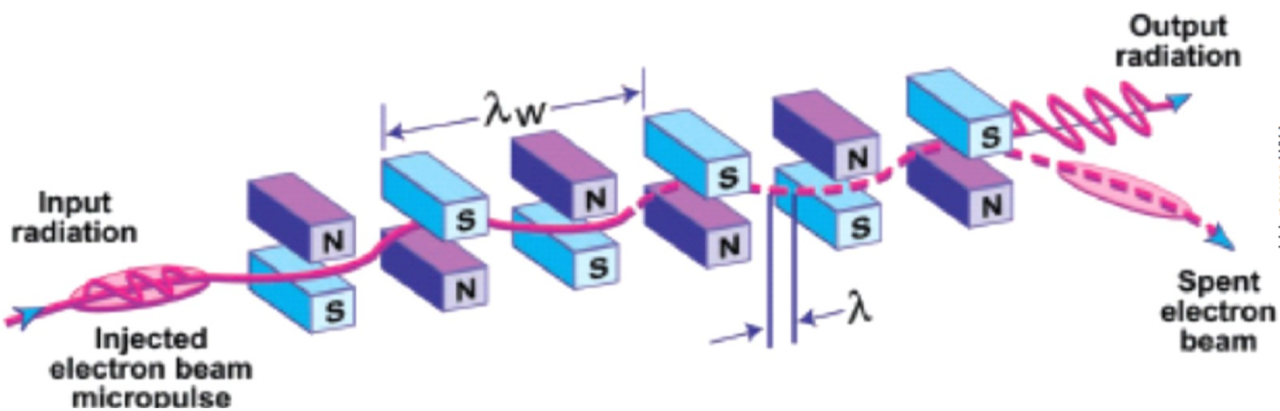
SASE-FEL

Self-Amplified Spontaneous Emission (SASE) –Free Electron Laser (FEL)

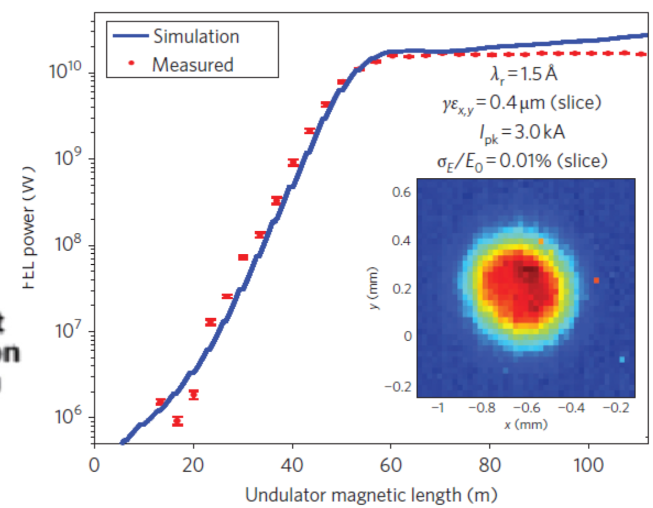
- FEL Power: exponential growth $P_{\mathrm{FEL}} = P_0 e^{z/L_g}$

  with Power Gain Length: $L_g = \frac{1}{\sqrt{3}}\left(\frac{2mc\gamma^3\sigma_x{}^2\lambda_u}{\mu_0 e K^2 \hat{I}}\right)^{1/3}$

$$K = 93.4 B_w \lambda_w$$



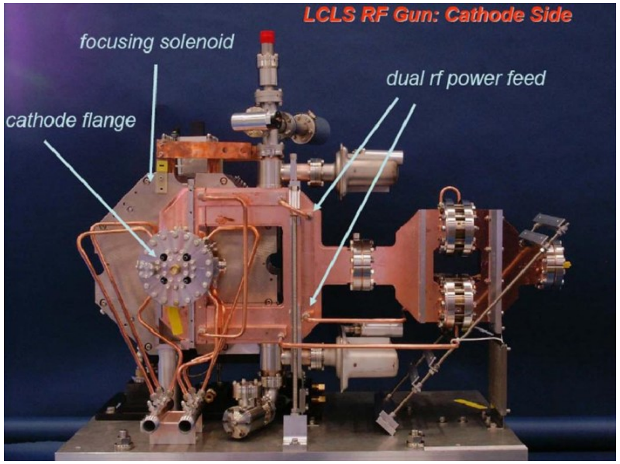
$$\lambda \propto \frac{\lambda_w}{\gamma^2}$$

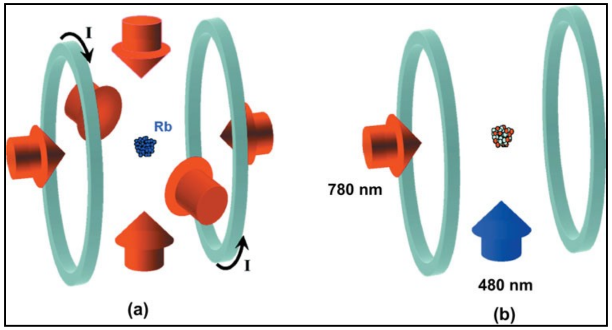


SASE-FEL

The advantages of using cold electron source

	Cold Atoms	Conventional
Charge Q (pC)	1	100
Repetition Rate (kHz)	1	0.12
Effective T (K)	10	5000
Effective kT (eV)	0.001	0.5
Norm. $\epsilon_\perp$ (mm-mrad)	0.013	0.5
rms size σ_x (mm)	0.026	1
Long. (keV ps)	1	40
Energy out of Gun (MeV)	0.1	6
Bunch length (fs)	10	30
Peak current (A)	100	3400
Electron Energy (GeV)	1.3	13.64
FEL wavelength (Å)	1	1.5





SASE FEL

Unlike the conventional laser

- FEL is quantum transition from momentum state
- From classical view point, this is the electron kinetic energy being converted into photon energy

However, the electron initial kinetic energy spread will be very large, if it is warm

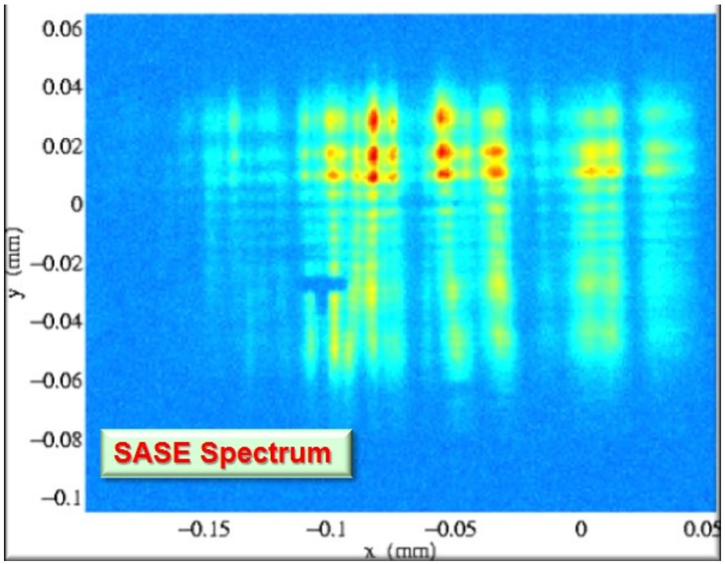
The corresponding FEL bandwidth will be large

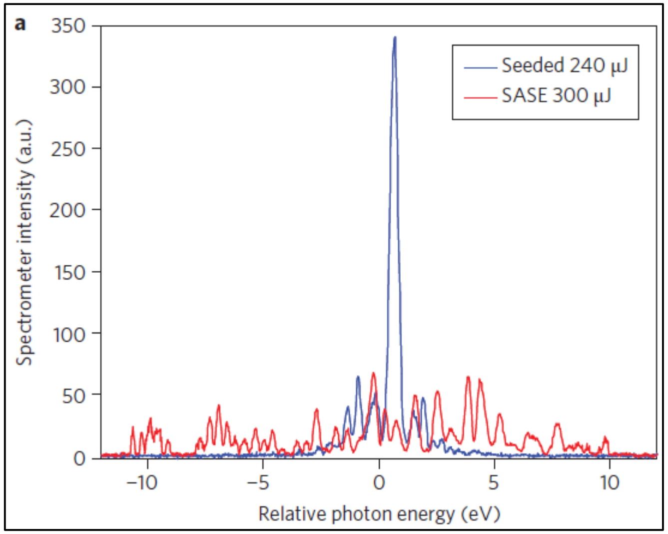
- Not a true laser

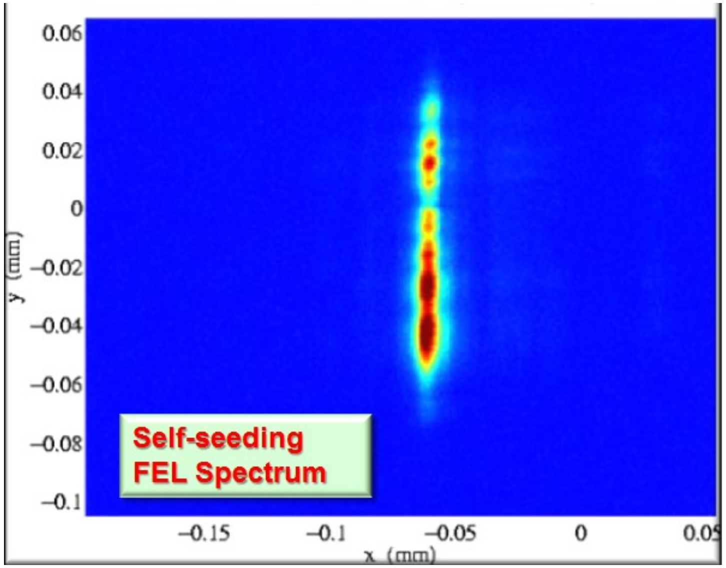
SASE FEL

Conventional SASE FEL spectrum: Spiky

- Number of spikes: the initial electron energy spread / full coherent spike bandwidth determined by pulse duration







QUANTUM FEL

High-gain free electron laser (FEL) and Collective atomic recoil laser (CARL)

- Self-bunching and exponential enhancement of the emitted radiation
- were originally conceived in a classical framework where the discrete nature of the recoil due to scattering of a photon by the particle was ignored, usually being masked by temperature effects
- In particular, with Bose-Einstein Condensates (BEC), it is necessary to describe the center-of-mass motion of the atoms in CARL quantum mechanically

In general, the classical limit for CARLs and FELs is obtained when the change of momentum of the particles is much larger than the quantum photon recoil $\hbar k$.

QUANTUM FEL

High-gain free electron laser (FEL)

- a relativistic high current electron beam with energy $mc^2\gamma_0$, injected in a magnet (``wiggler'') with a transverse, static magnetic field B_w and periodicity λ_u, which radiates in the forward direction at the wavelength $\lambda \sim \lambda_u(1 + a_w{}^2)/2\gamma_0{}^2$, where $a_w = eB_w/mc^2k_u$ is the wiggler parameter and $k_u = 2\pi/\lambda_u$

Collective atomic recoil laser (CARL)

- a collection of two-level atoms, driven by a far-detuned pump laser of frequency ω_p, which radiates at the frequency $\omega \sim \omega_p$ in the direction opposite to the pump

In both cases the radiation process arises from a collective instability which originates a symmetry breaking in the spatial distribution of the particles, i.e. a self-bunching of particles which group in regions smaller than the wavelength.

QUANTUM FEL

The FEL Hamiltonian for N electrons interactiong with a single mode of radiation field:

- $H = \sum_{j=1}^{N} \left[\frac{{p_j}^2}{2\bar{\rho}} + ig\left(a^+ e^{-i\theta_j} - a e^{i\theta_j}\right) \right] - \delta a^+ a$

where $\theta_j = (k + k_w)z - ckt_j - \delta\bar{z}$ and $p_j = mc\left(\gamma_j - \gamma_0\right)/[\hbar(k + k_w)]$are position and momentum operators of the jth electron, with $\left[\theta_j, p_j\right] = i\delta_{ij}$.

QUANTUM FEL

The quantum-mechanical dynamics of both FELs and CARLs can be described by a Schrödinger equation for the ``matter-wave'' field Ψ coupled self-consistently with the equation for the radiation field amplitude *A*:

$$i\frac{\partial\Psi(\theta,\bar{t})}{\partial\bar{t}} = -\frac{1}{\bar{\rho}}\frac{\partial\Psi^2(\theta,\bar{t})}{\partial\theta^2} - \frac{i\bar{\rho}}{2}\left[A(\theta,\bar{t})e^{i\theta} - c.c.\right]\Psi(\theta,\bar{t}),$$

$$\left(\frac{\partial}{\partial\bar{t}} + \frac{1}{\epsilon}\frac{\partial}{\partial\theta}\right)A(\theta,\bar{t}) = |\Psi(\theta,\bar{t})|^2 e^{-i\theta} + i\frac{\delta}{\bar{\rho}}A(\theta,\bar{t})$$

where θ is the phase of the particle, $\bar{t}$ is the dimensionless time, $|A|^2 = (2/N\bar{\rho})|a|^2$, where $|a|^2$is the average number of photons in the volume *V*, and $|\Psi(\theta,\bar{t})|^2$ is the space-time dependent particle density, normalized to unity.

QUANTUM FEL

Ψ: Fourier series

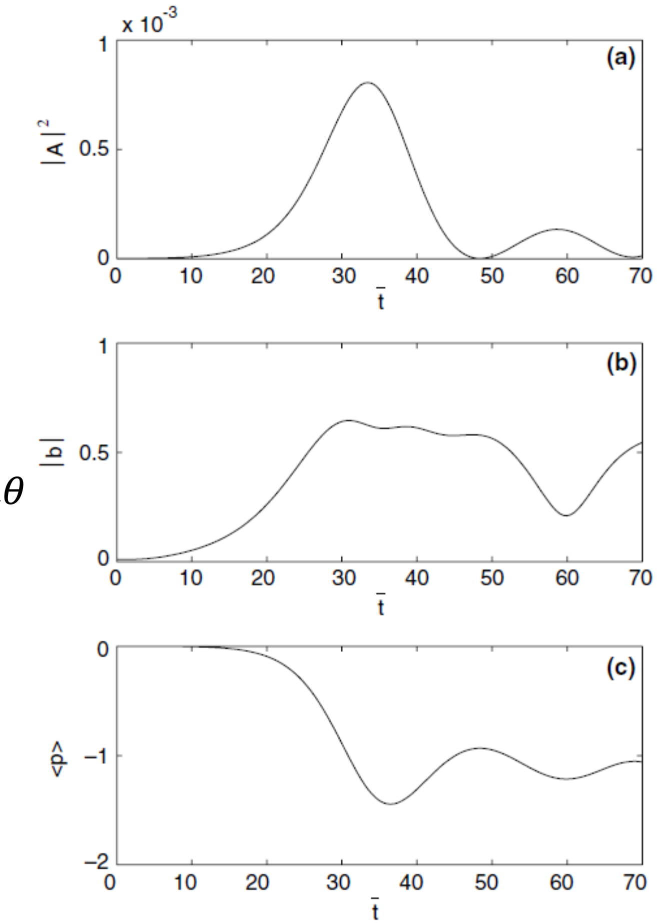
$$\Psi(\theta, z_1, \bar{t}) = \sum_{n=-\infty}^{\infty} c_n(z_1, \bar{t}) e^{in\theta}$$

the coupled equations:

$$\frac{\partial c_n}{\partial \bar{t}} = -\frac{in^2}{\bar{\rho}} c_n - \frac{\bar{\rho}}{2}\left(A c_{n-1} - A^* c_{n+1}\right),$$

$$\frac{\partial A}{\partial \bar{t}} + \frac{\partial A}{\partial z_1} = \sum_{n=-\infty}^{\infty} c_n {c_{n-1}}^* + i\frac{\delta}{\bar{\rho}} A$$

$$A \sim A e^{\varsigma \bar{t}}$$



- Cubic equation:
- $\left(\zeta - \frac{\delta}{\bar{\rho}}\right)\left(\zeta^2 - \frac{1}{\bar{\rho}^2}\right) + 1 = 0$

QFEL parameters

	Classical	**Quantum**
Charge Q (pC)	1	0.1
Undulator Strength K	0.1	0.5
Undulator Period λ_u (mm)	1.3	0.0008
Gain Length (m)	0.28	0.002
Norm. $\epsilon_\perp$ (mm-mrad)	0.013	0.001
rms size σ_x (mm)	0.026	1
Long. (keV ps)	1	0.1
Peak current (A)	100	0.001
Electron Energy (GeV)	1.3	0.015
FEL wavelength (Å)	1	3.9

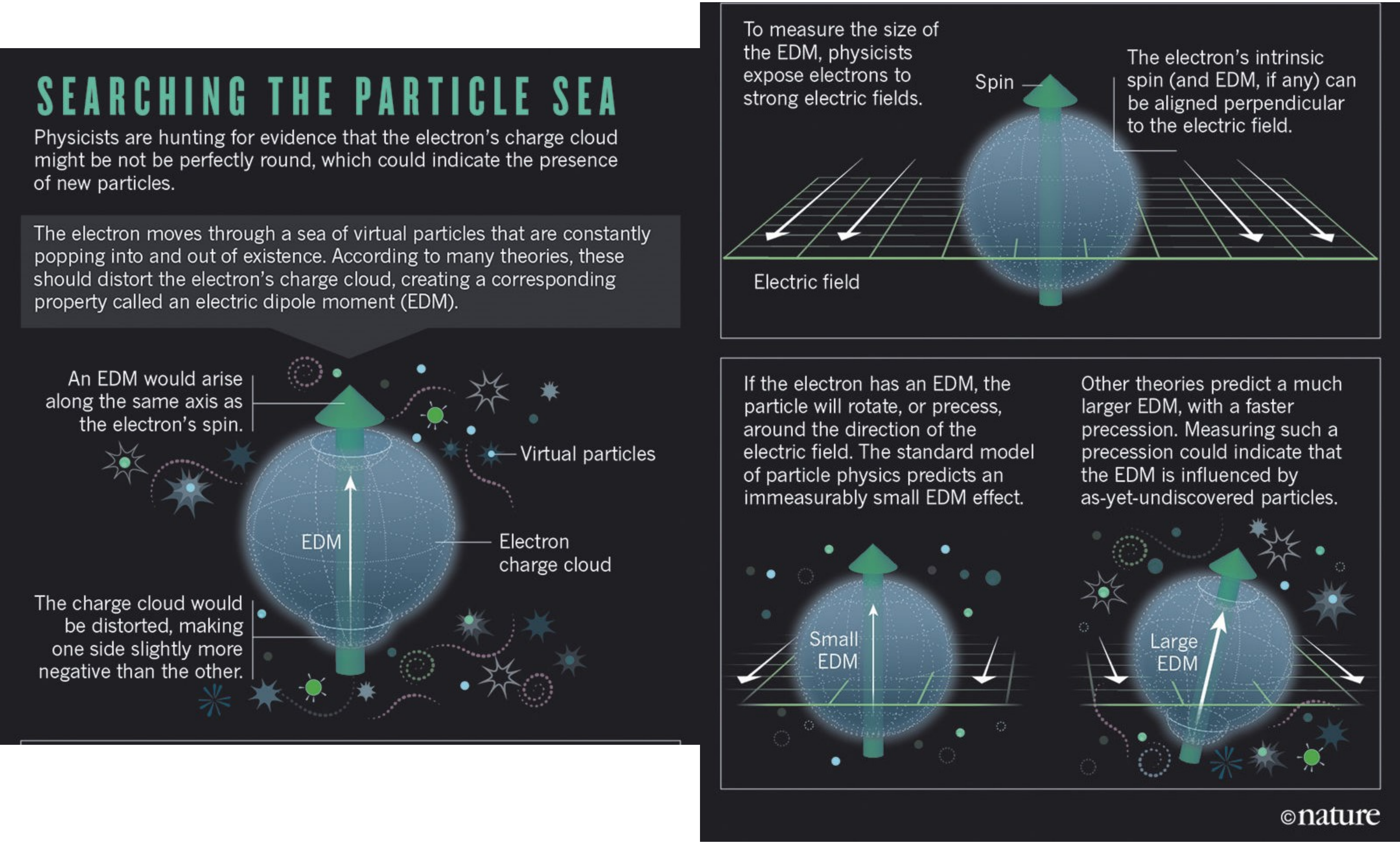
DISCUSSIONS

- Once we understand the fundamental physics, we can find novel solution, but not just follow what people are suggesting.
- Cold Atoms now relatively easy to obtain
- Cold electron from cold atoms can make free electron laser compact and work in the quantum regime

FUNDAMENTAL PHYSICS

G. Popkin, “TABLETOP PHYSICS PUSHED TO THE EDGE”, Nature 553, 142 (2018).

FUNDAMENTAL PHYSICS



FINAL REMARK: FEL FOR FUNDAMENTAL PHYSICS (FP) STUDIES

- Aspects of the FEL physics as FP:
  - The QED nature of the underlying laser mechanism;
  - Truly quantum signature in a process whose phenomenology is dominated by classical effects.
- The perspective uses of the FEL in FP experiments:
  - Non-linear effects in QED: photon–photon scattering;
  - Search for dark matter candidates like axions.

Progress in Particle and Nuclear Physics 99 (2018) 1–28

ELSEVIER

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

Review

Free electron laser and fundamental physics

Giuseppe Dattoli, Federico Nguyen *

ENEA – Fusion and Nuclear Safety Department, C.R. Frascati, Via E. Fermi 45 – 00044 Frascati, Roma, Italy

Check for updates