

Continued from page:

19/9/23

Lecture 1 → Fabrizio ←

NOTES → LSC1 ←

→ 1 student notes
phys

+ Paolo + amico di Paolo

Ytterbium laser to date

(bio-ind.)

→ Comput. chemistry ← modular as. theory

→ phd from Fontainebleau

photoacoustic

pump-probe STM

→ phd ~~from~~ Gregor

→ Paolo

→ phd Fei

[3-4 lec. Cover]

→ Sources of HHG ; as X-ray

→ Free-electron lasers

→ fs + as electron pulses ←

→ future developments ←

→ Defroging phase transition

1st order phase transition

PRA 2, 4, 9, 16

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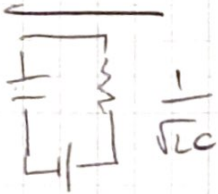
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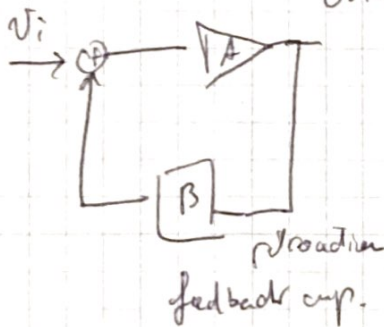
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OSCILLATOR



EL.

 $\frac{1}{m} \frac{d^2x}{dt^2} + f(T)$ MECHANIC

~~OPTION~~
OPTION


$$V_u = AV_i + ABV_u$$

$$V_u(1 - AB) = AV_i$$

$$V_u = \frac{A}{1 - AB} V_i$$

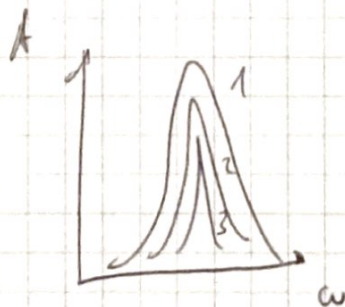
 TRANSFER FUNCTION
OF A
SYSTEM WITH

FEEDBACK ACTION

RING or LOOP gain

$$|BA| \leq 1$$

$$V_u = AV_i \sum_{n=0}^{\infty} (BA)^n$$



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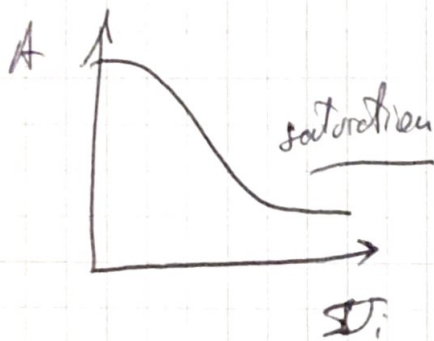
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 βA has to be conserved. $\rightarrow$ if $\beta A = 1$ bandwidth $\rightarrow 0$
 $G \rightarrow \infty$ } δ function

arbitrarily low

if $\beta A > 1$ above the threshold $\rightarrow$ infinite signal.

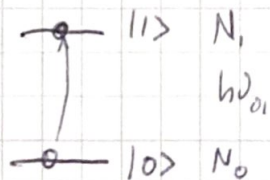
ingredients for the oscillator

① amplifier $\rightarrow$ Doppler.② retroaction $\rightarrow$ cavity.

generate radiation (photons)

accelerate charges $\rightarrow$ Bremsstrahlung
 $\rightarrow$ synchrotron radiation
 $\rightarrow$ dipole transitions

absorption



spontaneous emission

isotropic proton fluorescence

$$\frac{dN_1}{dt} = \sigma_{01}(\nu) \phi N_0$$

$\downarrow$ flux
 $\downarrow$ abs.
 $\downarrow$ x-section

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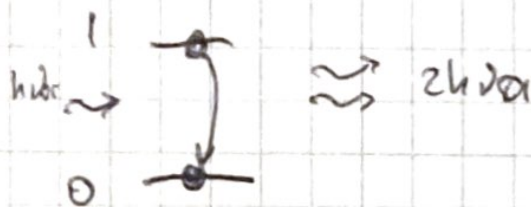
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$$\frac{dN_1}{dt} = A_{10} N_1$$

probability of spont. emission
rate

~~stimulated~~ emission



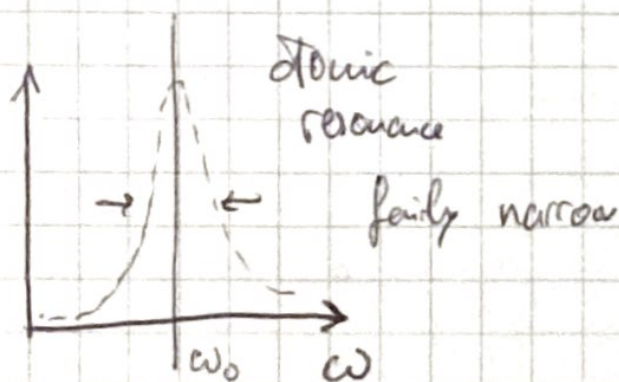
12 level system

$$\frac{dN_1}{dt} = A_{10} N_1 - \sigma_{01} N_1 \phi + \sigma_{01} \phi N_0$$

ϕ flux of photons has a spectrum $\phi(\nu)$

$$\frac{dN_1}{dt} = -A_{10} N_1 - N_1 \int \sigma_{10}(\nu) \phi(\nu) d\nu + N_0 \int \sigma_{01}(\nu) \phi(\nu) d\nu$$

APPROX



$\phi(\nu) \sim \text{constant}$
on the atomic
resonance

Lifetime broadened.

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$$\dot{N}_1 = -A_{10} N_1 + N_0 \phi(\nu_{01}) \int_V \sigma_{01}(\nu) d\nu - N_1 \phi(\nu_{10}) \int_V \sigma_{10}(\nu) d\nu$$

B_{01} B_{10}

Steady-state situation $\dot{N}_1 = 0$

$$\frac{\phi(\nu_{10}) B_{10} N_1}{c} + \frac{\phi(\nu_{01}) B_{01} N_0}{c} = A_{10} N_1$$

$$\phi(\nu_{10}) = \frac{A_{10} N_1 c}{B_{10} N_0 - B_{01} N_1}$$

density of
EM
energy

$$\phi(\nu_{10}) = \frac{P}{h\nu_{10}}$$

$$\rho = \frac{A_{10} c h \nu_{10}}{B_{10} \frac{N_0}{N_1} - B_{01}}$$

@ Planck eq.

$$\frac{N_1}{N_0} = e^{-\frac{E_{21}}{kT}} = e^{-\frac{h\nu_{01}}{kT}}$$

Black-body radiation
Planck

$$\rho(\nu_{01}) = \frac{h\nu_{01} A_{10}}{B_{01} e^{-\frac{h\nu_{01}}{kT}} - B_{10}}$$

$$\frac{8\pi h \nu_{01}^3}{c^3} \frac{1}{e^{\frac{h\nu_{01}}{kT}} - 1}$$

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OK done

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$$B_{10} = B_{01}$$

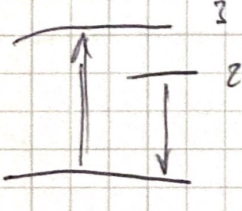
$$N_1 > N_0 \quad N_0 < N_1$$

absorption

Baron

The other Baron is
(~~the~~ ~~Baron~~ his son)

31



$$A_{32} \gg A_{21}$$

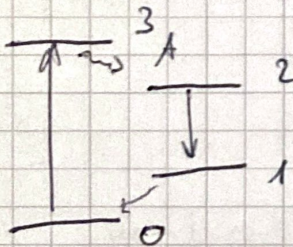
Find a favorable
situation

Ruby laser

(check) and explain a bit
Ruby down??

4-level system

$$A_{32}, A_{10} \gg A_{21}$$



$$\tau_{dec} \sim \lambda^3$$

In laser cavity run UV lasers.

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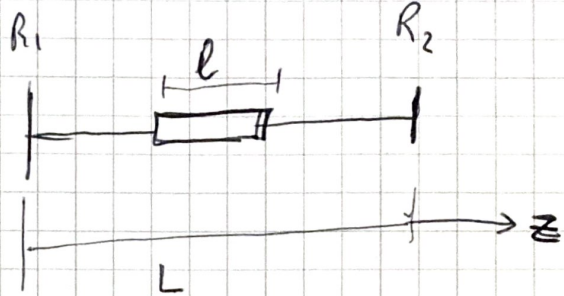
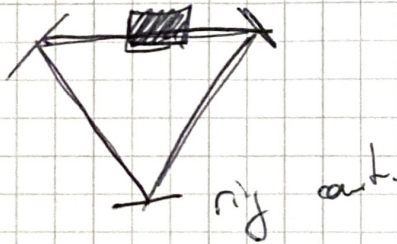
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Lasing Threshold for a 4 level system

How to build?

population inversion. ΔN

Approx: plane wave in the cavity

$$E_0 e^{i(\omega t - z k)}$$

$$z=0$$

$$E_0 e^{i\omega t} e^{-i\frac{\omega}{c} 2(L-l)}$$

$$n = \frac{\omega}{c} n$$

$$E_0 e^{i\omega t} e^{-i(n' + i n'') \frac{\omega}{c} z}$$

after 1 roundrip (2L)

$$E_0 e^{i\omega t} e^{-i\frac{\omega}{c} 2(L-l)} e^{-i(n' + i n'') \frac{\omega}{c} 2l} \quad r_1 r_2 = E_0 e^{i\omega t}$$

$$r_1 = \sqrt{R_1} e^{i\phi_1}$$

$$r_2 = \sqrt{R_2} e^{i\phi_2}$$

$$E_{2L} = E_0$$

if we want to be at Threshold

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$$|r| = 1$$

phase $2q\pi$

$$\alpha(\nu) = \sigma_{12} (N_2 - N_1)$$

gain per unit length

$$h'' = \frac{\sigma_{12} (N_2 - N_1)}{2\omega}$$

due to

$$|r| = 1 \quad \sqrt{R_1 R_2} e^{\alpha(\nu)l} = 1$$

$$\phi \rightarrow 2q\pi = \frac{2\pi}{c}$$

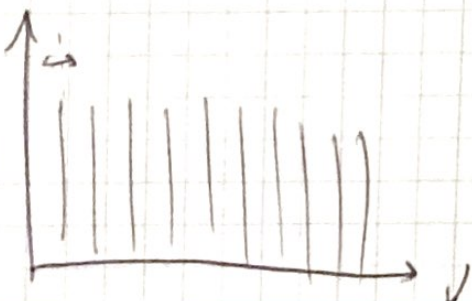
$$e^{\alpha_{thr} l} = \frac{1}{\sqrt{R_1 R_2}}$$

$$\alpha_{thr} = \frac{1}{l} \ln \frac{1}{\sqrt{R_1 R_2}}$$

optimum transmission?

$$L' = L - l + n'l \quad \text{optical path}$$

$$\nu_q = q \frac{c}{2L'} \quad \text{not loop freq. is allowed}$$



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MODES of FABRY PÉROT CAVITY

possible exercise

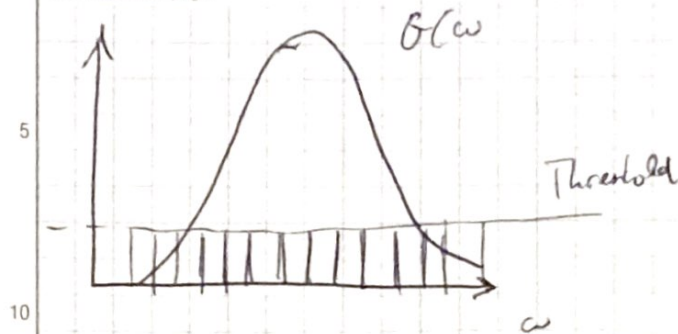
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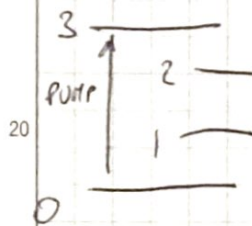
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RATE EQ. FOR THE 4 LEVEL SYSTEM



$$\begin{cases}
 N_0 + N_1 + N_2 + N_3 = N_t \\
 \frac{dN_2}{dt} = W_{03} (N_0 - N_3) - (A_{30} + A_{31} + A_{22} + \dots) N_3 \\
 \frac{dN_2}{dt} = A_{32} N_3 - (A_{21} + A_{23}) N_2 - \sigma \phi (N_2 - N_1) \\
 \frac{dN_1}{dt} = A_{31} N_3 + (A_{21} N_2) + \sigma \phi (N_2 - N_1) - A_{10} N_1
 \end{cases}$$

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lec 3

3/10/23

ARS

free lasers

free plasma laser

Free-electron laser

Dye-lasers

vibronic lasers

[color center?]

patented by Beyer '800

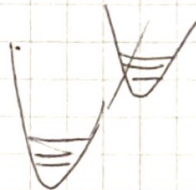


aromatic molecules

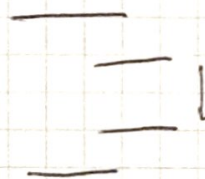


RADICALS

Dissolved in a liquid solvent.



vibronic state



fast transitions!

4-level system

low efficiency, high pump power

Ask

Adriana

Toxic + liquid technically complicated due to the liquid

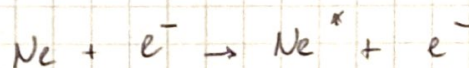
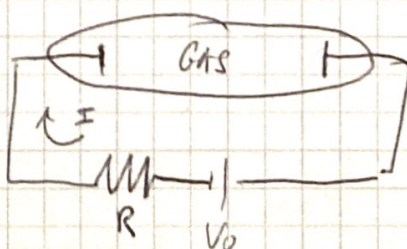
He-Ne

laser

Non-optical pop. inversion

(in the SC laser was done with a e^- current)

potential candidate Ne with fountain



low WE

problem to get the pop. inversion. you excite also other levels! harder

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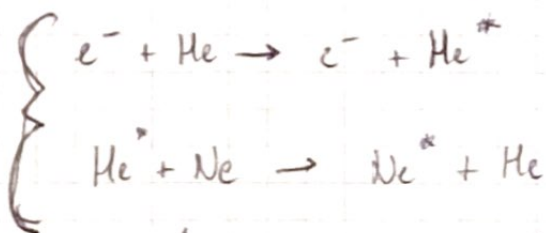
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With Ne does not work : Why?

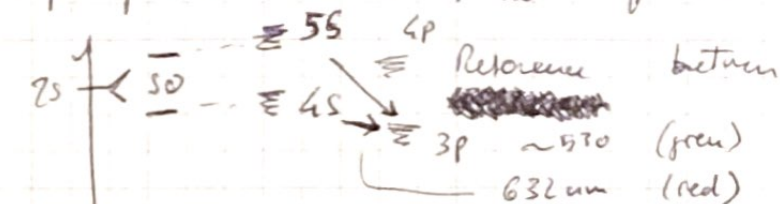
Mixture of He-Ne

→ electronic excitation



2-step process

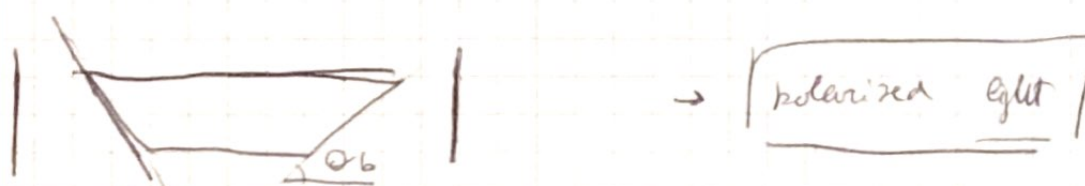
↑ This is more efficient



He ↑ 34 μm

4s → 3p 1.5 μm

? a lot of confusion here

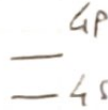


bandwidth as good as 50 kHz

→ Here an idea about the width

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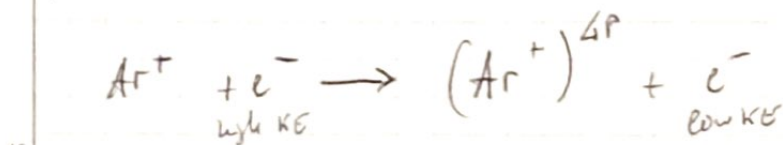
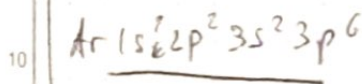
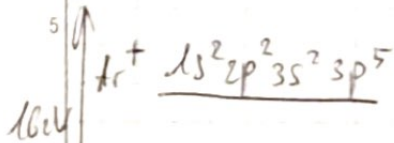
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~~Ar~~ Ar laser

$$\lambda \approx 550 \text{ nm}$$

It requires the Ar

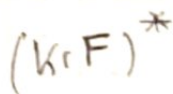
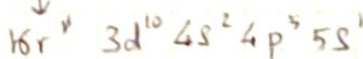
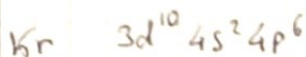
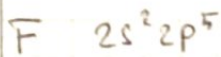
10W

low x-section 1-2 Amps of current

2-10 W of power are possible (natural pump lasers for Ti:Sapphire and dye lasers)

Excimer

{ molecule which won't exist in the GS but only in the excited state

~~Excimer~~ - mainly created by electron current in the gas

excited krypton

shortly-lived excited state

low

$$\lambda \sim 248 \text{ nm}$$

$$\eta \sim 2\%$$

kW

cm

Lithography

→ Fiber gratings

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CO₂ boxes mostly used by car companies to cut their heat

- Huge amount of power at long wavelengths

→ Machinery

In the CO₂ transition is not electronic; is a vibrational transition

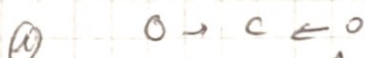
N - N covalent bond - no dipole

Na - ~~Cl~~ Cl very ionic bond → ~~small~~ dipole

+ -

~~CO₂~~ CO₂

frequency



longitudinal

ν_1



transverse

ν_2



long. asymmetric

ν_3

④ greenhouse - ~~effect~~ effect. black body radiation of the earth

~~Total energy~~ Total energy

$$E_T = h\nu_1 (N_1 + \frac{1}{2}) + h\nu_2 (N_2 + \frac{1}{2}) + h\nu_3 (N_3 + \frac{1}{2})$$

$N=3$ $3N-6$ 3 modes

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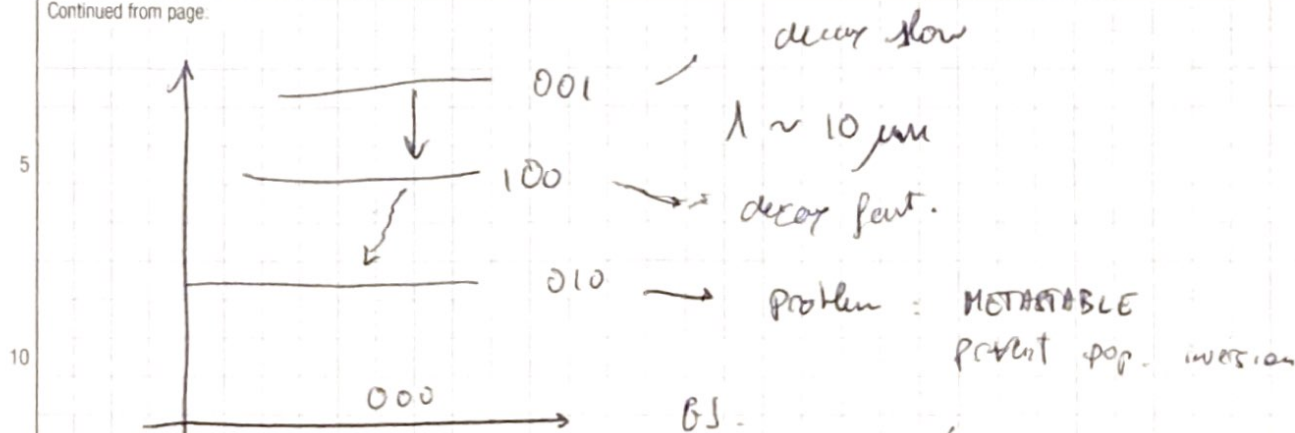
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(N_1, N_2, N_3)

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Solution: Mix CO_2 with N_2

N_2 can only decay collisionally.

Luckily the N_2 vibrates are in resonance with the one of CO_2 !

→ good mixture 1 CO_2 1 N_2 1:1 : 8

He

Also the He is important

$\eta \sim 20\%$

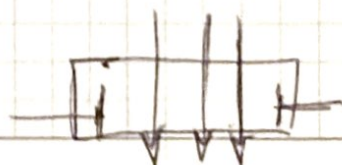
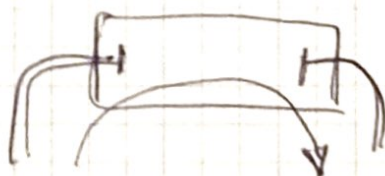
10-20 W

UP TO

KW

in certain schemes

flow direction



nozzle

sudden adiabatic
expansion
↓
cooling.

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pulsed lasers

HF

 H_2

+ F

 $\rightarrow$ HF^*

→ automatically in
pop. inverted
state

 $3 \mu m$

power level in the MW

Free-electron laser

 $\rightarrow$

up to the hard x-rays

Invent around the world

--- some hints

LASER

particle accelerators

energy momentum

 E, p

$$E_e \rightarrow h\nu + E_e'$$

$$p \rightarrow \hbar \vec{k} + Q$$

Idea in electrons

to radiate photons

RELATIVISTIC ELECTRON DYNAMICS

$$W = \sqrt{m_0^2 c^4 + c^2 p^2}$$

$$p = \frac{mv}{\sqrt{1 - v^2/c^2}}$$

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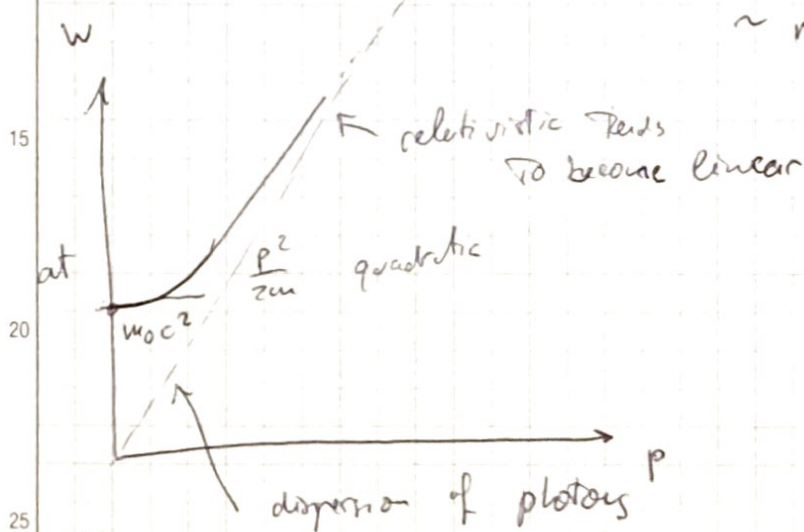
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at rest.
 $\hookrightarrow W = mc^2$

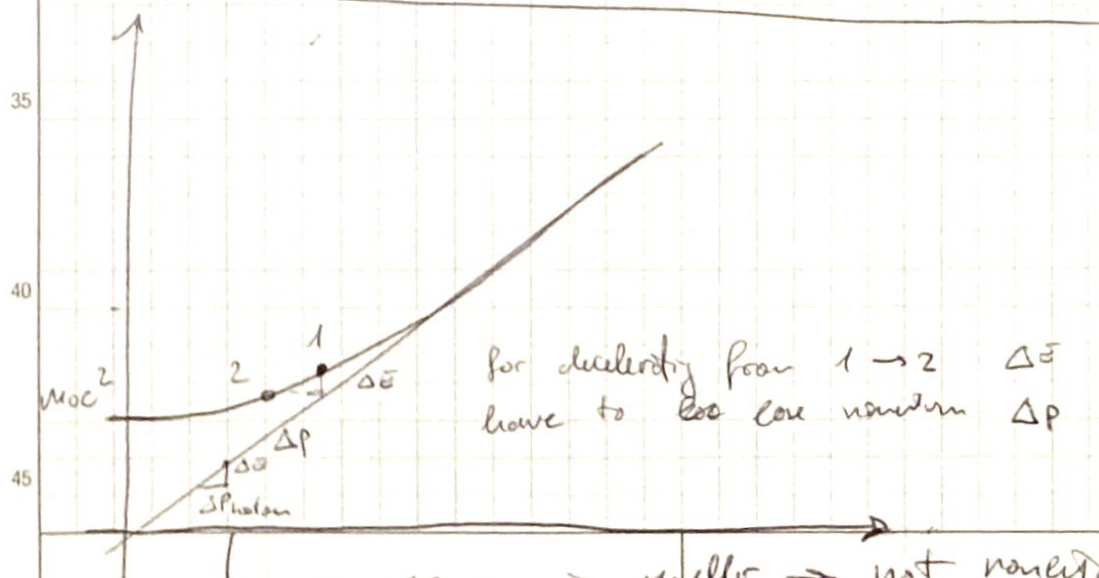
slow
 $\hookrightarrow \frac{c^2 p^2}{m^2 c^4} \ll 1 \Rightarrow W \sim mc^2 \left(1 + \frac{1}{2} \frac{p^2}{mc^2} \right)$

$\sim mc^2 + \frac{1}{2} \frac{p^2}{m}$



$$p = \frac{h}{\lambda} = \frac{h \nu}{c} = \frac{h \nu}{c}$$

Relativistic



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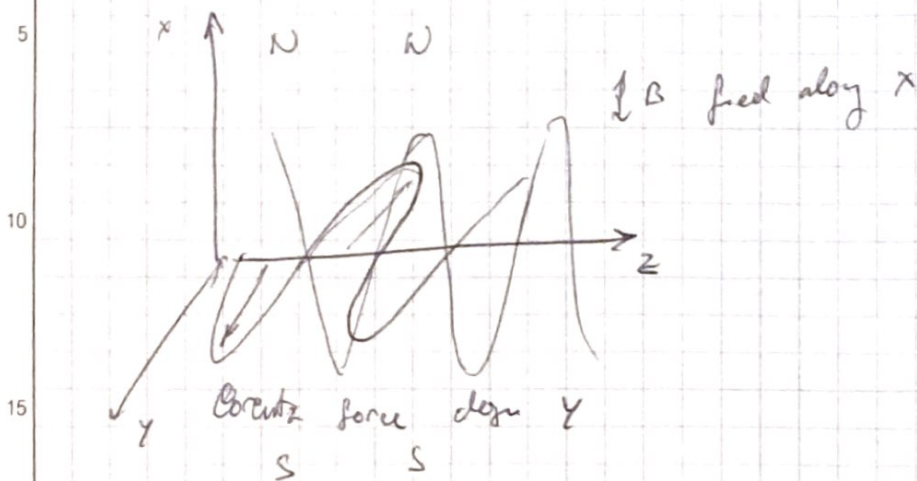
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How to overcome this problem?

periodic magnetic modulator

• intuitively: the wiggling gives the electron momentum kicks!

 e^- emits a photon at $z = z_0$ " " " " at $z = z_0 + \lambda$

$$t = \frac{\lambda}{v_z}$$

$$\frac{\lambda}{v_z} c \text{ to get } \lambda$$

electron slower than the photon!

$$\frac{\lambda}{v_z} c - \lambda = \lambda$$

$$\lambda = \lambda \left(\frac{c}{v_z} - 1 \right)$$

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$$\lambda \sim 1 \mu\text{m} \Rightarrow \frac{c}{v_g} - 1 \sim 10^{-4}$$

Typically infrared or vis ?

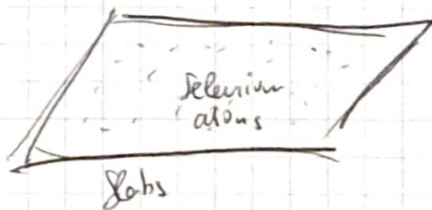
X-ray solid laser

→ not very clear ←

Se²⁴⁺

$$\lambda = 20 \text{ nm}$$

↓ Not laser.



→ high long. wave

10/10/23

How to generate pulses :

4 level system

Q-switching

Quality factor

— N_2

$$N_2 - N_1 = N$$

population inversion

— N_1

$$N_1 \sim 0$$

$$\begin{cases} \dot{N} = R_p - BQN - \frac{N}{\tau} \\ \dot{Q} = BQaNQ - \frac{Q}{\tau_c} \end{cases} \rightarrow \text{photon lifetime}$$

$$R_p = W_r (N_t - N)$$

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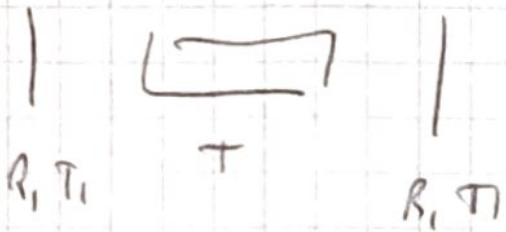
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$$\delta_1 = -\ln R_1 \quad \delta_2 = -\ln R_2$$

$$\delta = -\ln(1 - T)$$

$$\delta_i = -\ln(1 - T)$$

$$\tau_{\text{roundrip}} \sim \frac{2L}{c} \sim 6 \text{ ns}$$

$$R_2 \sim 90\%$$

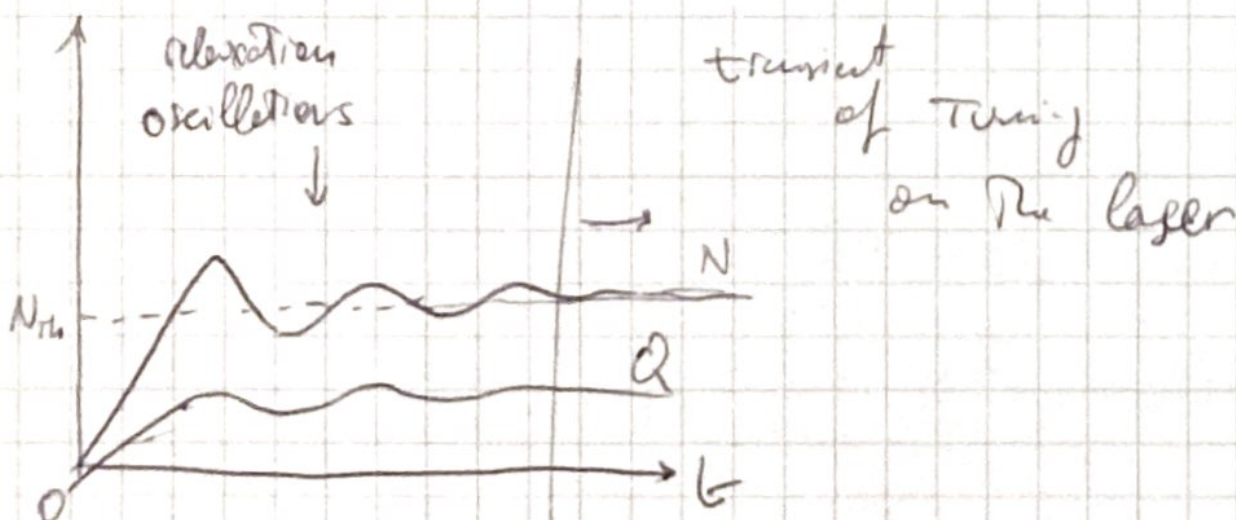
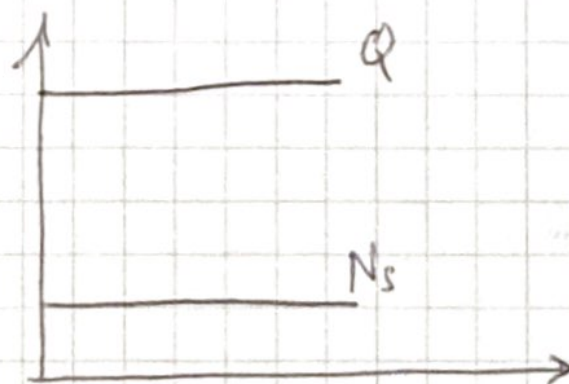
$$\tau_c \sim 60 \text{ ns}$$

$\tau_c \gg \tau$ lifetime of the electron system

$$\dot{Q} = 0$$

$$\dot{N} = 0$$

$$N_s \cong \frac{1}{\beta' V a \tau_c}$$



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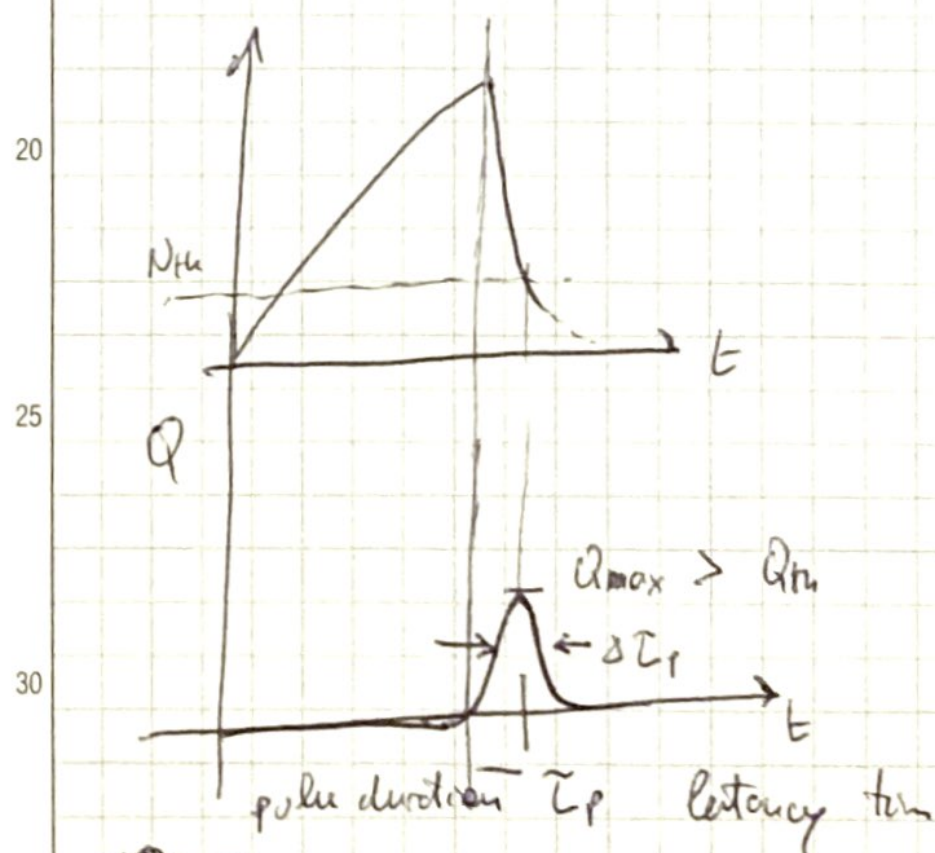
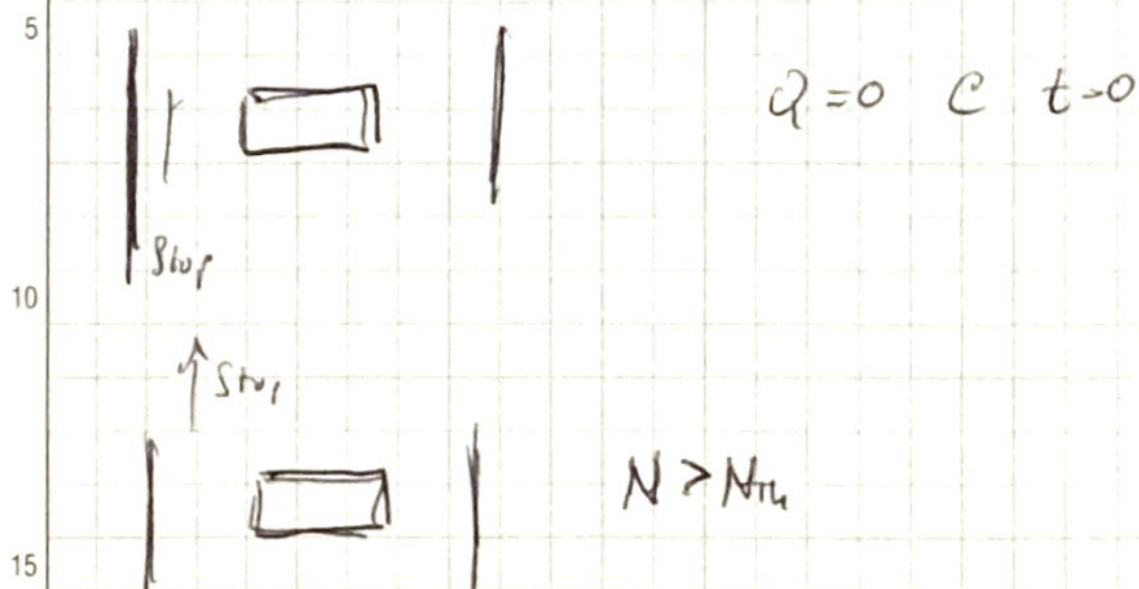
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Can we use this to get a pulse? Q switching.



~~scribble~~

ΔT_p pulse duration

$$T_p \ll T_{pump} \sim ms$$

duration of the pump lasers

$$T_p \ll T_{atom}$$

(300 ps)

During the generation of the pulse we can consider:

→ Neglect spontaneous emission during the Q-switching.

$$\sim \begin{cases} \dot{N} = -\beta AN \\ \dot{Q} = \nu_a \beta AN - Q/\tau_c \end{cases}$$

Neglect also the pumping term.

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(is a max) at the $t=t_p$ max $\Rightarrow$

$$Q_{0 \approx} N_p(t_p) = \frac{1}{\beta \nu_a \tau_p}$$

ratio of the eq.

Continued from page.

$$\frac{\dot{Q}}{\dot{N}} = \frac{N_a \beta Q N - Q/\tau}{-\beta Q N} = -v_a + \frac{1}{\beta Q N}$$

$$= v_a \left(-1 + \frac{N_p}{N} \right)$$

$\int_{N_{\text{initial}}}^N \rightarrow$ total amount of photons

$$Q_p = v_a N_p \left[\frac{N_a \tau}{N_p} - \ln \left(\frac{N}{N_p} \right) \right]$$

$\downarrow$ magic number how in capacitor in cavity.

$\Delta \tau_p$ & τ_c

$$\tau_p \sim (3-10) \tau_c$$

$\uparrow$ latency time

shorter cavity lead to shorter pulses

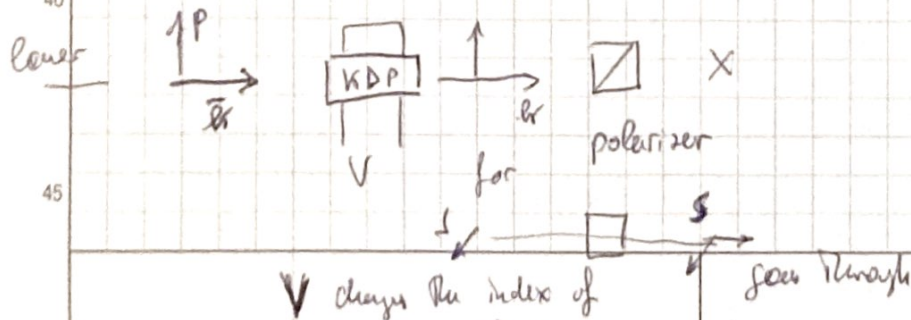
Q-switching methods

~~1ms~~ — 100 ns

How to Q-switch a laser

$\rightarrow$ Pockels effect $\leftarrow$ KDP ; LiNbO_3

electro optic switch



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$$n \propto V$$

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Saturable absorber

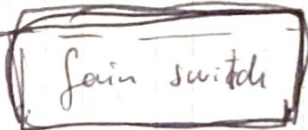
passive



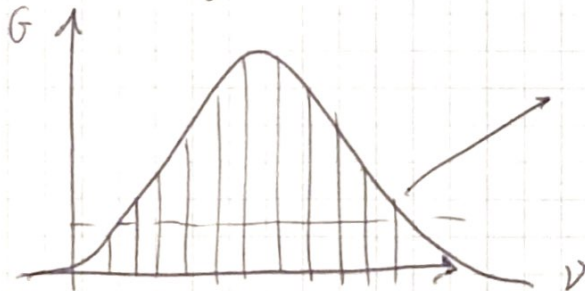
copy ~~of~~ ^{the} explanation

→ have to RE-DO it

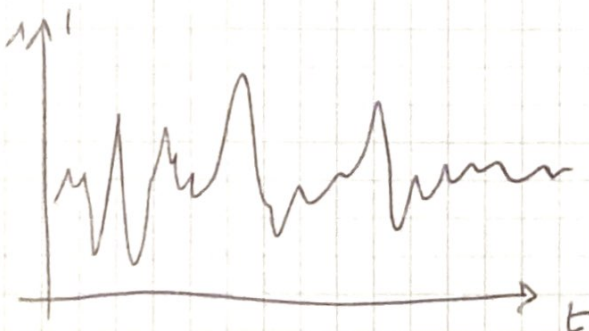
$\tau_{abs} \sim \tau_{asat}$



→ pulse the population in. itself

Mode-Locking.

different phases for each mode

Multistable

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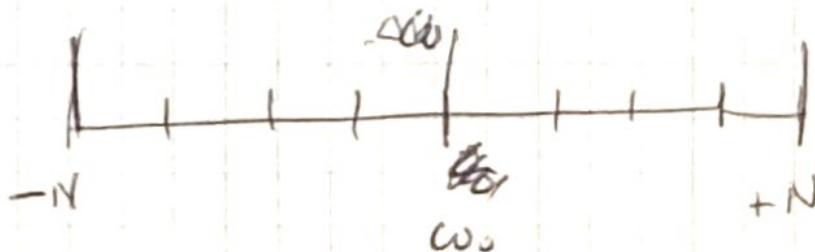
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$$E(t) = \sum_l E_l e^{i\omega_l t} e^{i\phi_l}$$

What happens if 1 "lock" the phase of modes

$\phi_l = \text{constant}$.

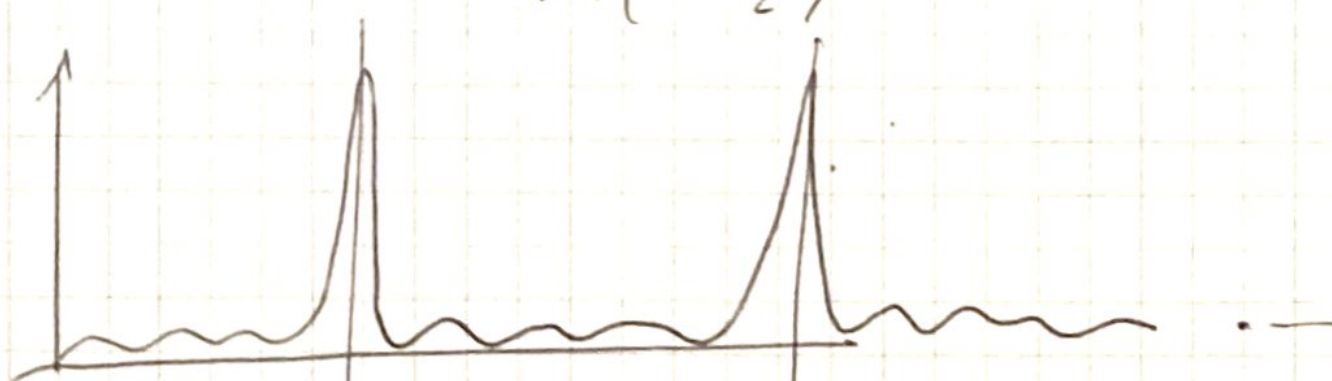
$$E_l = E_0$$



$$E(t) = \sum_{m=-N}^N E_0 e^{i(\omega_0 + m\Delta\omega)t + m\phi}$$

geometrical sum

$$A(t) = E_0 \frac{\sin[(2N+1)\Delta\omega t]}{\sin(\Delta\omega t/2)}$$



$$\Delta\tau_p \sim \frac{1}{N\Delta\omega}$$

$$\tau_p \sim \frac{2L}{c}$$

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→ Coupled oscillators ←

→ Back house Resonator →

2 el. oscillator

↓
if coupled
eventually they will
lock in phase



↑ need to increase the coupling
of radiating atoms

$$\Delta \tau_p \sim \frac{1}{\Delta \nu}$$

broadband

⇒ short pulses.

Dye
Ti:Sapphire

P.A. flow

$$\tau_p \sim \frac{2L}{c}$$

rep rate $\sim 10^5$ MHz

Harriet all lay cavity oscillator

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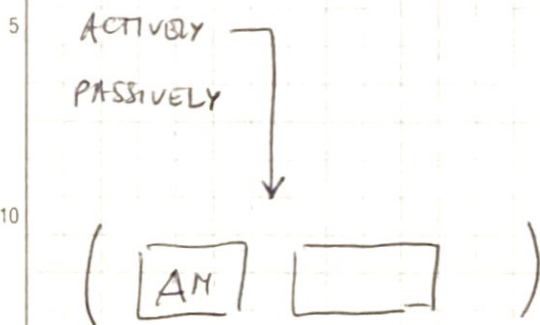
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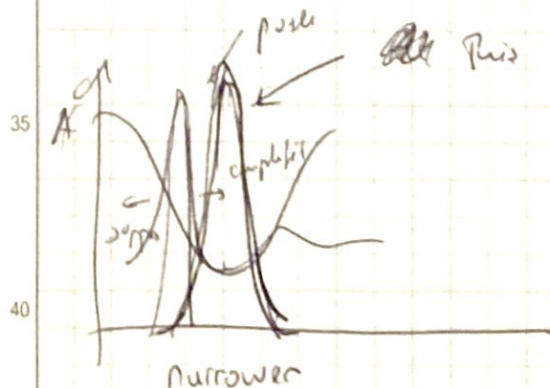
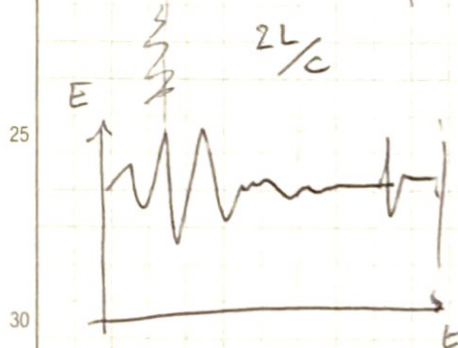
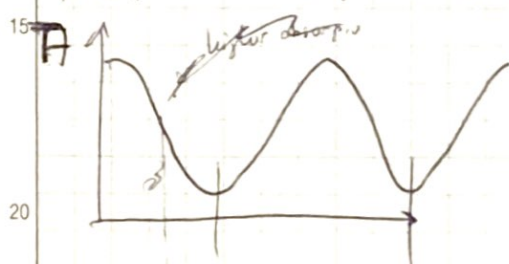
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How do you make lock?



$A = 1 - T$ amplitude modulation

just have to
calculate P_{res}
at the cavity
round trip time



At this depletes the N all of a sudden

TIME DOMAIN PICTURE
OF ACTIVE
MODE LOCKING

only the pulse at the right time survive
the same is for the other modes

45

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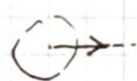
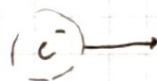
→ ETH Z → Steve Johnson Lect. 1 ←

x-ray source $\lambda \approx 1 \text{ \AA}$

(accelerator-based)

- 1) Inverse Compton sources
- 2) Undulators / Synchrotrons
- 3) FEL
- 4) electron accelerators GeV
- 5) → Smith-Purcell ←
 - Transition radiation
 - Cherenkov radiation
 - Atom-based

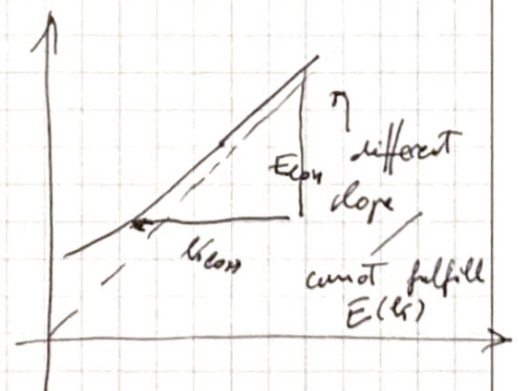
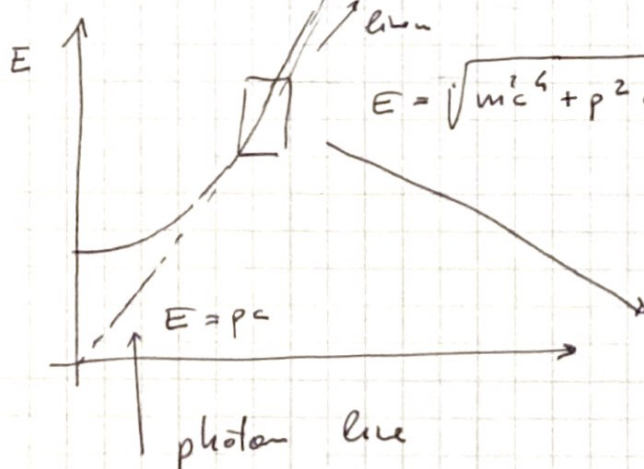
1) Inverse-Compton scattering.



emit a photon?

 $\sim h\nu$

how to conserve energy and momentum?



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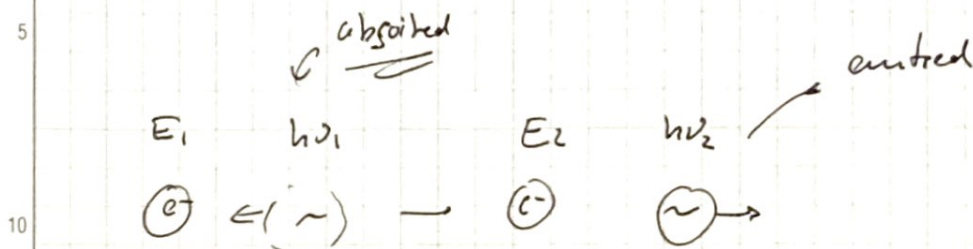
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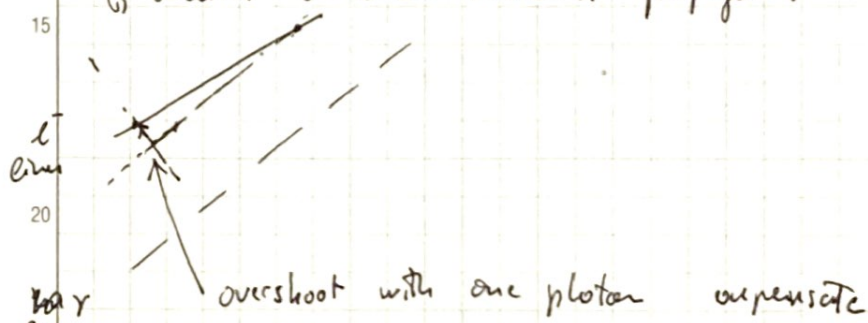
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The process becomes possible if I add a photon



add this photon

Which direction should it propagate?



counter-propagate a beam of photons (VIS)

INVERSE COMPTON SCATTERING

$$\Delta E = E_1 - E_2 \approx \frac{dE}{dp} \Delta p \leftarrow (p_1 - p_2)$$

(positive)

electron momentum change

$$\frac{1}{2E} 2pc^2 = \frac{pc^2}{E} = \frac{\gamma h\nu c^2}{\gamma mc^2}$$

cross check

$$\frac{p_1 c^2}{E_1}$$

$$\Delta E = h\nu_2 - h\nu_1$$

Compton

$$\Delta p \approx \frac{h\nu_2}{c} + \frac{h\nu_1}{c}$$

photon change

careful this is
so in the other
direction.

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$$h\nu_2 - h\nu_1 = \frac{p_1 c}{E_1} \frac{h}{c} (\nu_2 - \nu_1)$$

$$\cancel{\nu_2} = \frac{(1 + \frac{p_1 c}{E_1})}{1 - \frac{p_1 c}{E_1}} \nu_1 = \frac{(1 + \frac{v_1}{c})}{(1 - \frac{v_1}{c})} \nu_1$$

(and $\gamma \approx 1$)from $(1 + v/c) \sim 2$

$$\nu_2 \approx \frac{(1 + v/c)}{(1 - v/c)} \nu_1 \approx 4\gamma^2 \nu_1$$

$$\gamma \approx 1$$

$$\gamma^2 = \frac{1}{1 - v^2/c^2}$$

For very large γ we can convert IR photons to x-rays
What parameters do you need?

$$\lambda_1 \sim 1 \mu\text{m}$$

$$\lambda_2 = 1 \text{ \AA}$$

What γ do we need for that?

relationship for λ_s ?

reciprocal

$$\lambda_2 = \frac{1}{4\gamma^2} \lambda_1$$

$$\gamma = \frac{1}{2} \sqrt{\frac{\lambda_1}{\lambda_2}} \sim \frac{1}{2} \sqrt{\frac{10^{-6}}{10^{-10}}} = \frac{1}{2} 10^2 = 50 \sim 50$$

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Not Expt 8

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Electron energy?

$$E_1 = 50 (0.5 \text{ MeV}) \approx 25 \text{ MeV}$$

also

→ ok for fairly compact sources.

How much can you push it? Astrophysics can make x-rays

 λ : small compared with the rest mass

How to do in practice? → deflect momentum

→ Tilt a bit the beam (easily done, $\sim 90^\circ$)We did not do the derivation in terms of θ

"COMPACT X-RAY SOURCES"

UNDULATORS "Kink" synchrotron scattering careful: not 1:1 correspondence (SYNCHROTRON)

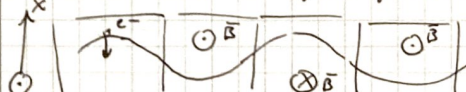
Classical limit

↑ classical wave propagating in that direction
 • electron will propagate in a zig-zag sinusoidal path

you can consider it classically & obtain similar effects

UNDULATOR → static magnetic force

use the Lorentz force $\vec{F} = -e \vec{v} \times \vec{B} = \frac{d\vec{p}}{dt}$ (relativity (radius of the wave))



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v →

PERIODIC ARRAY OF MAGNETS

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Approximate the B field (it is discontinuous...)

$$B_y = B_0 \cos\left(\frac{2\pi}{\lambda} z\right)$$

periodicity
of B field

This results to
harmonics
of the oscillation

$$\frac{d\vec{p}}{dt} = -e\vec{v} \times \vec{B}$$

~~But~~ we will solve it for the momentum.

Assumptions:

$$p_z \gg p_x$$

"weak"

perturbation
of traj.

$$p_y = 0 \quad (2d \text{ problem})$$

due to the
B field

$$p_x(z_e) = p_x^{(0)} \sin\left(\frac{2\pi}{\lambda} z_e\right)$$

guess
solution

z coordinate of
the electron
along his traj.

$$\frac{dp_x}{dt} = p_x^{(0)} \cos\left(\frac{2\pi}{\lambda} z_e\right) \frac{dz_e}{dt} \frac{2\pi}{\lambda}$$

$$\approx \frac{2\pi}{\lambda} \bar{v}_z p_x^{(0)} \cos\left(\frac{2\pi}{\lambda} z\right)$$

what is z_e ?
Approximation

oscillating a bit

$$\frac{dz_e}{dt} \approx \bar{v}_z$$

on
AVERAGE

Let's equate to the Lorentz force

$$p_x = p_x^{(0)} \sin\left(\frac{2\pi}{\lambda} z\right)$$

$$-e v B_0$$

$$\Rightarrow p_x^{(0)} = \frac{-e v B_0 \lambda}{2\pi \bar{v}_z}$$

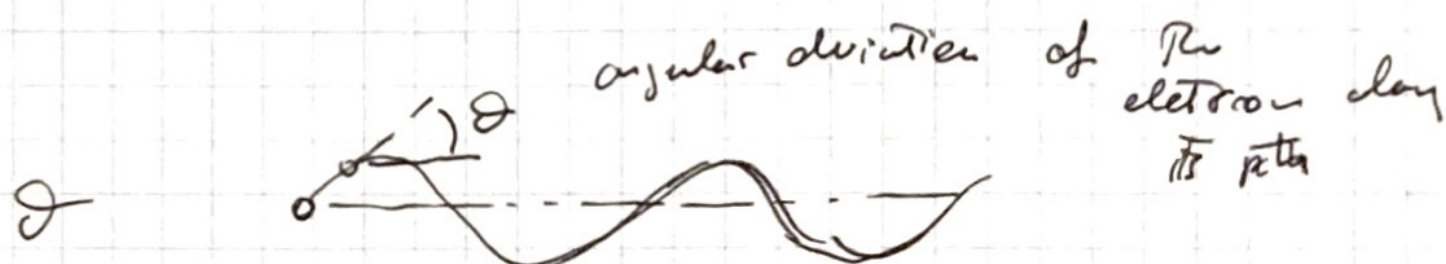
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What does this mean in Tbm. of the trajectory?

 $\vec{B}$ cannot do work on the electron $\rightarrow$ TOTAL momentum constant~~Ex~~

$$p = \text{constant} \frac{Q}{\omega} = \sqrt{p_z^2 + p_x^2}$$

This implies that the z components oscillate

$$\theta = \frac{p_x}{p_z} \approx \frac{p_x}{p} \quad p_x \text{ small.} \quad = \frac{-e B_0 v}{2\pi p \frac{v}{v_z}} \lambda \sin\left(\frac{2\pi}{\lambda} z_c\right)$$

in our approx of small oscillations this holds

(Typically $\lambda \sim \text{cm}$)maximum deviation. θ_{max} Typically we express it ~~as~~ as a function of K parameter of the undulator

$$\theta_{\text{max}} \equiv \frac{K}{\gamma} = \frac{-e B_0}{2\pi \gamma m v} \frac{v}{v_z} \lambda$$

 K - PARAMETER

is a "strength" parameter

$$K = \frac{e B_0 \lambda}{2\pi m c}$$

$$v_z \sim c$$

ratio of angular excursion and the angle of radiation in

 K small undulator

(interference of light is important)

 K large wiggler

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$$v_z = \frac{p_z}{\gamma m} = \frac{p}{\gamma m} \sqrt{1 - \left(\frac{p_x}{p}\right)^2}$$

↑
correction factor to the p_z relative to p

$$= \cancel{v} \sqrt{1 - \frac{K^2}{\gamma^2} \sin^2\left(\frac{2\pi z_e}{\lambda}\right)}$$

total velocity → express it as function of β

$$\beta = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \Rightarrow 1 - \frac{v^2}{c^2} = \frac{1}{\beta^2} \Rightarrow v = c \sqrt{1 - \frac{1}{\beta^2}}$$

$$v_z = c \sqrt{\left(1 - \frac{1}{\beta^2}\right) \left(1 - \frac{K^2}{\gamma^2} \sin^2\left(\frac{2\pi z_e}{\lambda}\right)\right)}$$

↓ clock

$$\approx c \left(1 - \frac{1}{2\beta^2} \left(1 + K^2 \sin^2\left(\frac{2\pi z_e}{\lambda}\right)\right)\right)$$

drop the terms
with $\frac{1}{\beta^4}$

expand and do Taylor series of the v

approx. expression of the inst. velocity

what is the average $\bar{v}_z$ we used before

$$\sin^2\left(\frac{2\pi z_e}{\lambda}\right) \rightarrow \frac{1}{2}$$

$$\bar{v}_z = c \left(1 - \frac{1}{2\beta^2} \left(1 + \frac{K^2}{\gamma^2}\right)\right)$$

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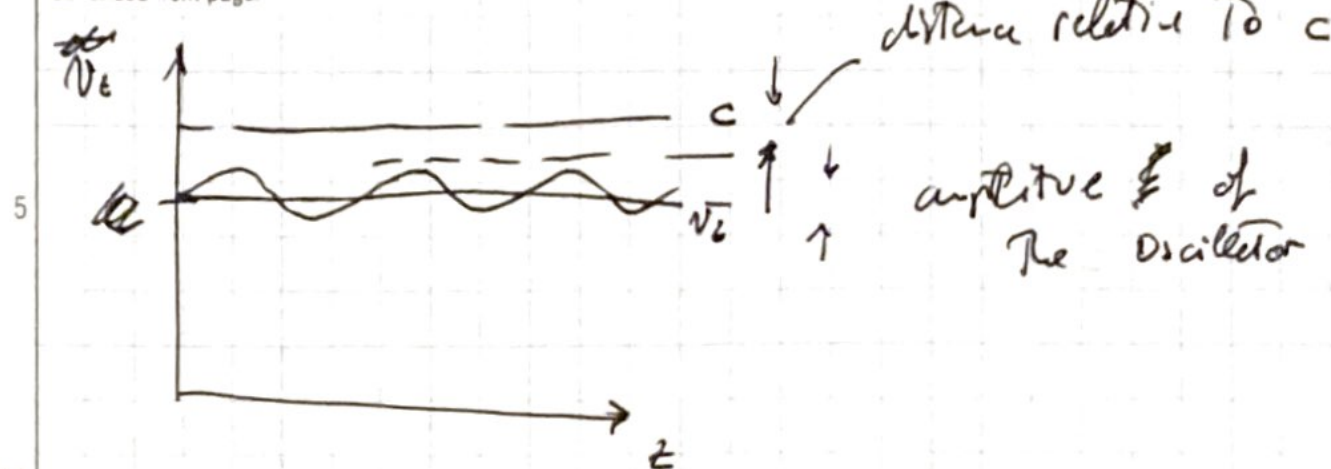
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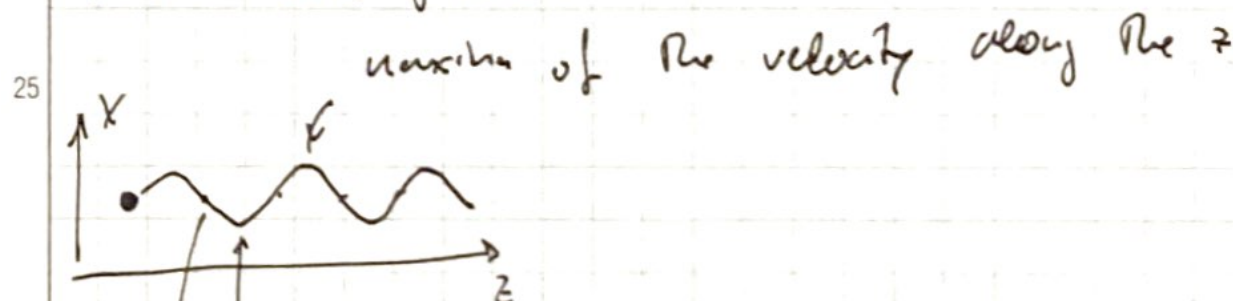


SHIFT OF THE FRAME OF REF. $\Rightarrow$ IMAGINE OF MOVING TO THE REF. FRAME WHERE THE e^- MOVES A MINIMUM AMOUNT FRAME $\bar{v}_z$

$v = \bar{v}_z$ Lorentz shift.

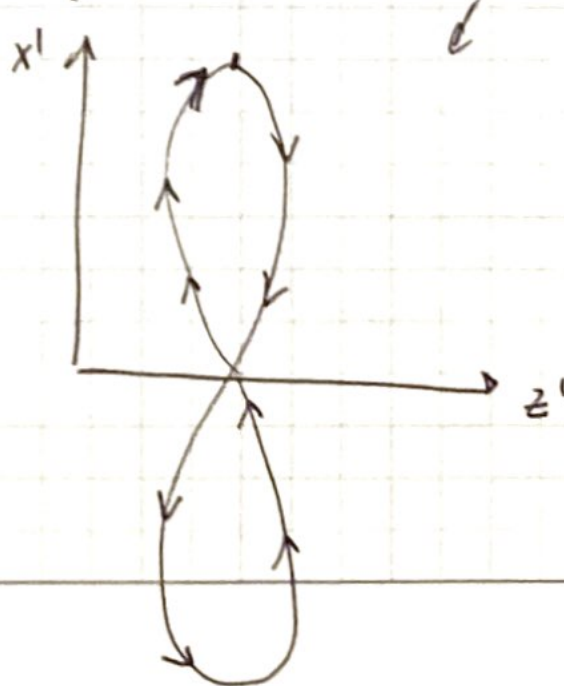
what is the motion looking like in this frame.

In the lab. frame:



zero-velocity. velocity along $v_z = \bar{v}_z \Rightarrow$ no net displacement

In the $\bar{v}_z$



This is a figure of 8 path originating from the $u \omega^2$ (different periodicity)

often approx with dipole (Larmor)

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width much smaller

radiation

$\rightarrow$ in the far field

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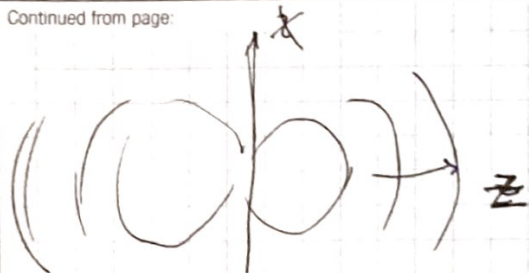
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NODE along x axis

larger for larger K

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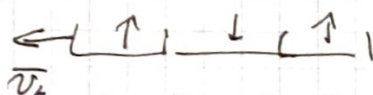


Take the radiation and shift it back to the other frame to get the shape?



What is the period T' of this motion in the moving frame?

period of the moving magnets in this frame



Lorentz contraction of 1

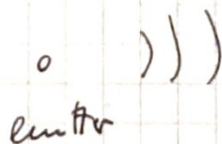
$$T' = \frac{\Lambda'}{\bar{v}_z} = \frac{\Lambda \sqrt{1 - v_z^2/c^2}}{\bar{v}_z} = \frac{1}{\bar{v}'}$$

Reference frame shift back to the lab. frame
Relativistic doppler shift

$$\nu = \nu' \sqrt{\frac{1 + \bar{v}_z/c}{1 - \bar{v}_z/c}}$$

(check relation with β)

This is an upshift



Observer



emitter

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Flip it to get the λ

$$\lambda = \sqrt{\frac{1 - \bar{v}_1/c}{1 + \bar{v}_2/c}} \lambda'$$

$$\lambda' = \frac{c}{\nu'}$$

$$= \cancel{\frac{c}{\nu_2}} \frac{c}{\nu_2} \sqrt{1 - \frac{\bar{v}_2^2}{c^2}} \sqrt{\frac{1 - \bar{v}_1/c}{1 + \bar{v}_2/c}}$$

(--- math)

approx. to be made

$$\lambda \approx \lambda \left(\frac{1}{2\gamma^2} \left(1 + \frac{k^2}{2} \right) \right)$$

large: contraction + doppler shift

example.

$$\lambda = 1 \text{ \AA} \quad \lambda = 1 \text{ cm} \quad \Rightarrow \quad \gamma \sim 10^4 \quad \left(\text{much higher than Compton} \right)$$

 $\Downarrow$

$$E \sim 5 \text{ GeV}$$

 $\longrightarrow$ questions on emission directivity $\longrightarrow$ question on circular polarization
(mentioned apple 2 polariz.)

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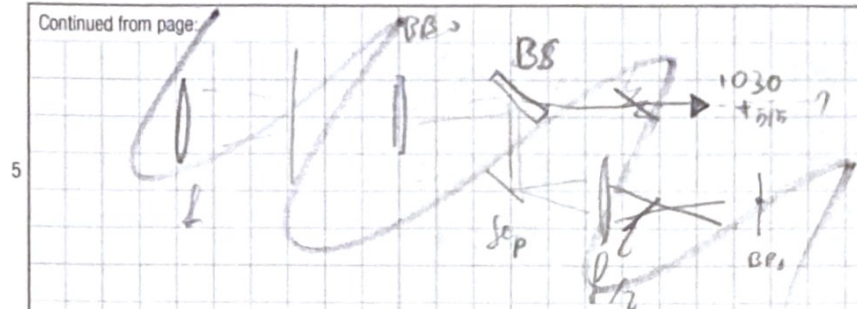
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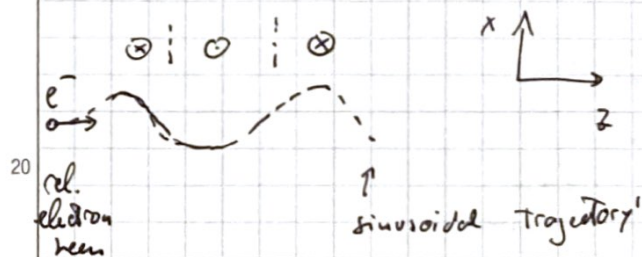
14/11/23

Steve

Lecture 2

→ Undulators ←

lab frame : un - primed frame



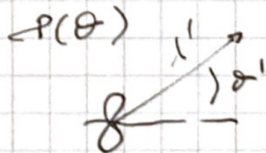
- "primed" frame moving with the $\bar{v}_z$ average z -velocity
 - relativistic transform



figure of 8 trajectory

magnets $\bar{v}_z$ velocity of the magnets (note you get also an $\vec{E}$ field)

(Transform + doppler shift.)

power distribution as function of θ  $P(\theta) \propto \cos^2 \theta K^2$ essentially dipole radiation

• length + acceleration of the electrons

Scales with the K parameter ($E \propto K$)
 ($P \propto K^2$)

related to the amplitude of the motion.

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• now we are allowing $\theta \neq 0 \Rightarrow k_x', k_z'$

wavevector!
not the
 $\vec{k}$

$$k_x' = k' \sin \theta'$$

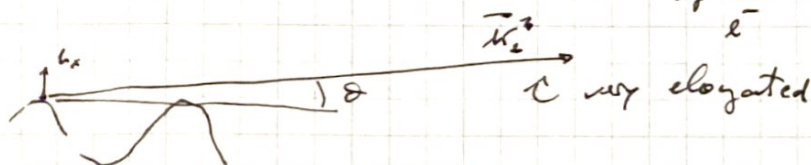
$$k_z' = k' \cos \theta'$$

$$k_x = k_x' = k' \sin \theta' \quad (\text{orthogonal to the shift})$$

$$k_z = k_z' \left(\frac{1 + \frac{v_z}{c}}{1 - \frac{v_z}{c}} \right)^{1/2} \approx 2\gamma k' \cos \theta' \left(1 + \frac{v_z^2}{c^2} \right)$$

or is elongating by a factor γ "Doppler"

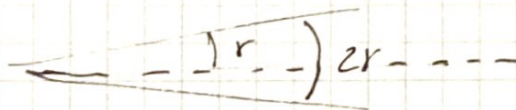
gamma factor
of the
electron
actual
velocity
of the
 e^-



radiation is very well collimated; close to be tangential to the

$$\theta \sim \frac{k_x}{k_z} \approx \frac{1}{2\gamma} \tan \theta'$$

did not understand
"line effect"



• wait you can have interference effect when?

if angular deviations are smaller than $\frac{1}{2\gamma}$

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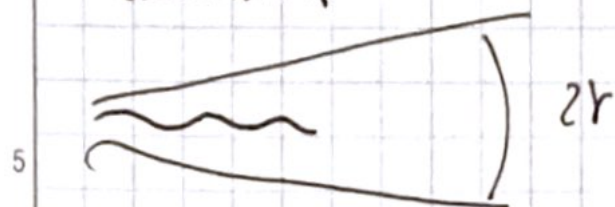
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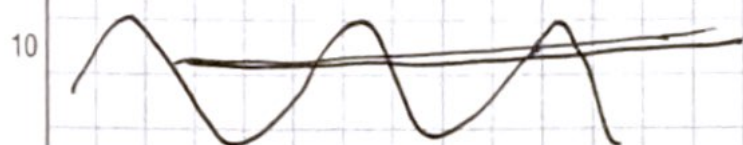
UNDULATOR



YES INTERFERENCE

→ cone is narrower

WIGGLER



LESS NO INTERFERENCE (LESS..)

Slope of the line
→ cone width

(Sketch here)

$$\frac{1}{\sqrt{N}}$$

Typically 20 in a synchrotron

Source comparison:

Key parameters ~~of~~ of various source

INVERSE COMPTON

$$\lambda_2 = \frac{1}{4\gamma^2} \lambda_1$$

→ easily ~ 1 μm

UNDULATOR

$$\lambda = \frac{1}{2\gamma^2} \lambda_1 \left(1 + \frac{K^2}{2} \right)$$

why undulator and not the Compton?

→ ~~at~~ at non
~ mm

Power is very different.

$$P_{und} \propto K^2 \propto B_0^2 \lambda^2$$

$$P_C \propto \frac{E_0^2 \lambda^2}{4\gamma^2 c^2}$$

penalty in the power of $1/\gamma^2$!!

in the inverse Compton scattering you can also define a K parameter!

$$K_{IC} \approx \frac{e E_0 \lambda_1}{c} \sqrt{\frac{1 - v/c}{1 + v/c}} \frac{1}{2\pi m_e c} \leftarrow \text{Doppler shifted}$$

$$K_{und} = \frac{e B_0 \lambda}{2\pi m_e c}$$

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~ 1/28

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Slides about the MS

 $B_0 \rightarrow$ function of
of the gap.

TUNING CURVES

Boillanc

 $\frac{p_h}{5(0.17 \text{ BW})}$ steady
OPTICS
INVARIANT

"spectral density"

$$\frac{\Delta\lambda}{\lambda} 10^{-3}$$

you cannot
increase
by focusing

you also include the divergence

QUESTION OF "SPECTRAL MODES"

compressed electrons
100 ps $\rightarrow$ 10 ps

you have been rapidly
and inject more often

beams are larger ...

FEL Typically 10^{10} more flux

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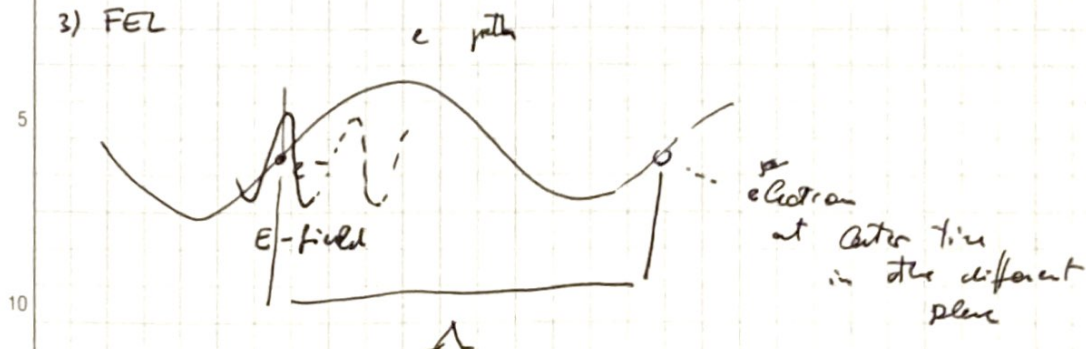
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3) FEL



We need to consider the interaction of the electron with the $\vec{E}$ field

→ approx sinusoidal; uniform...

$$\Delta z = \Lambda$$

$$\Delta t = \Lambda / v_z$$

↙ electric field in the undulator

$$\vec{E}(z, t) = E_0 \sin(\omega t - k z)$$

GOAL → AMPLIFY

CONDITION FOR ENERGY TRANSFER BETWEEN $\vec{E}$ AND $\vec{v}$

WORK DONE BY ELECTRIC FIELD

$$dW = -e \underbrace{\vec{E} \cdot d\vec{s}}_{\text{force}}$$

ASSUME TRAJECTORY NOT PERTURBED A LOT..

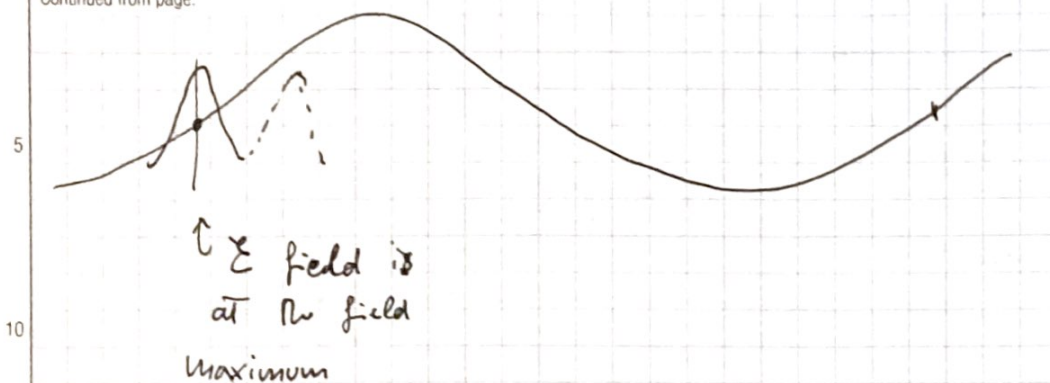
CONDITION WHICH MAKE THIS PERIODIC

IF $dW > 0$ ~~loss~~ gain (electron gain energy)
 $dW < 0$ ~~gain~~ loss
 ↑ in the $\vec{E}$ field

WE WANT THE $\vec{E}$ IN PHASE

Continued to page:

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$$\omega \Delta t - k \Delta z = 2\pi n$$

phase difference

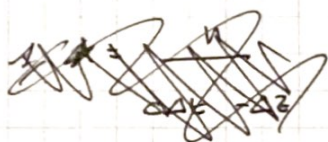
$$\Delta z = \lambda$$

$$\Delta t = \lambda / v_e$$

$$\omega = kc$$

dispersion relation

$$k(c \Delta t - \Delta z) = 2\pi n$$



$$k = \frac{2\pi}{\lambda} = \frac{n \cdot 2\pi}{c \Delta t - \Delta z}$$

$$\lambda = \frac{c \Delta t - \Delta z}{n}$$

$$= \frac{\lambda}{n} \left(\frac{c}{v_e} - 1 \right)$$

This is the resonance condition

$$\lambda \sim \frac{\lambda}{n} \frac{1}{2\gamma^2} \left(1 + \frac{\gamma^2}{2} \right)$$

correspondence between λ and the electron interaction

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as long as λ is matched to undulator

← weak →

ANIMATION

FOR

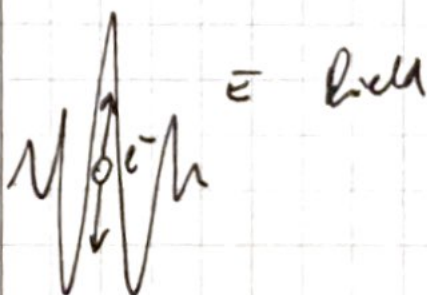
$\Delta W > 0$

and

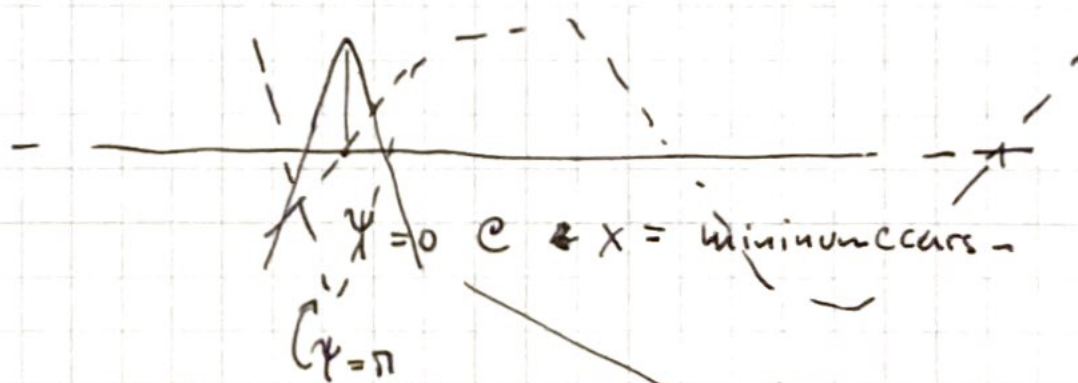
$\Delta W < 0$

shift by

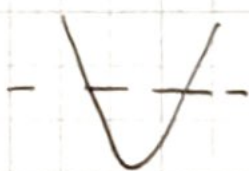
π



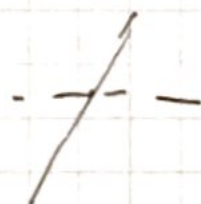
ponderomotive phase $\psi = 0$



$\psi = \pi$



$\psi = \pi/2$



$\psi = 3\pi/2$



ψ	Energy flow	FEL
0	$e^- \rightarrow \text{light}$	GAIN COM
π	$\text{light} \rightarrow e^-$	
$\pi/2$	NO NET TRANSFER	
$3\pi/2$	" " "	

"LOW * GAIN" FEL

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we have to correct for ~~the~~ changing amplitude
 (we derived the "low gain" condition

$$\hookrightarrow \frac{d\mathcal{E}_0}{dz} \ll \frac{\mathcal{E}_0}{\lambda}$$

HIGH GAIN REGIME $\Rightarrow$ ^{MICRO} ~~PLASMA~~ BUNCHING

FOR $\psi = 0 \rightarrow e^-$ ~~are~~ ^{lose} energy $\rightarrow \gamma$ decreases
 $\psi = \pi \rightarrow e^-$ gaining energy $\rightarrow \gamma$ increases

γ change $\Rightarrow \psi$ change

FLOW OF THE POSITIVE PHASE

TRANSITION TO A COHERENT ADDITION REGIME

SUPER RADIANT

$N P_0$

$N^2 P_0$

seeding vs SASE

$\hookrightarrow$ here we started with an e^- field

FIRST FEL started with spontaneous emission

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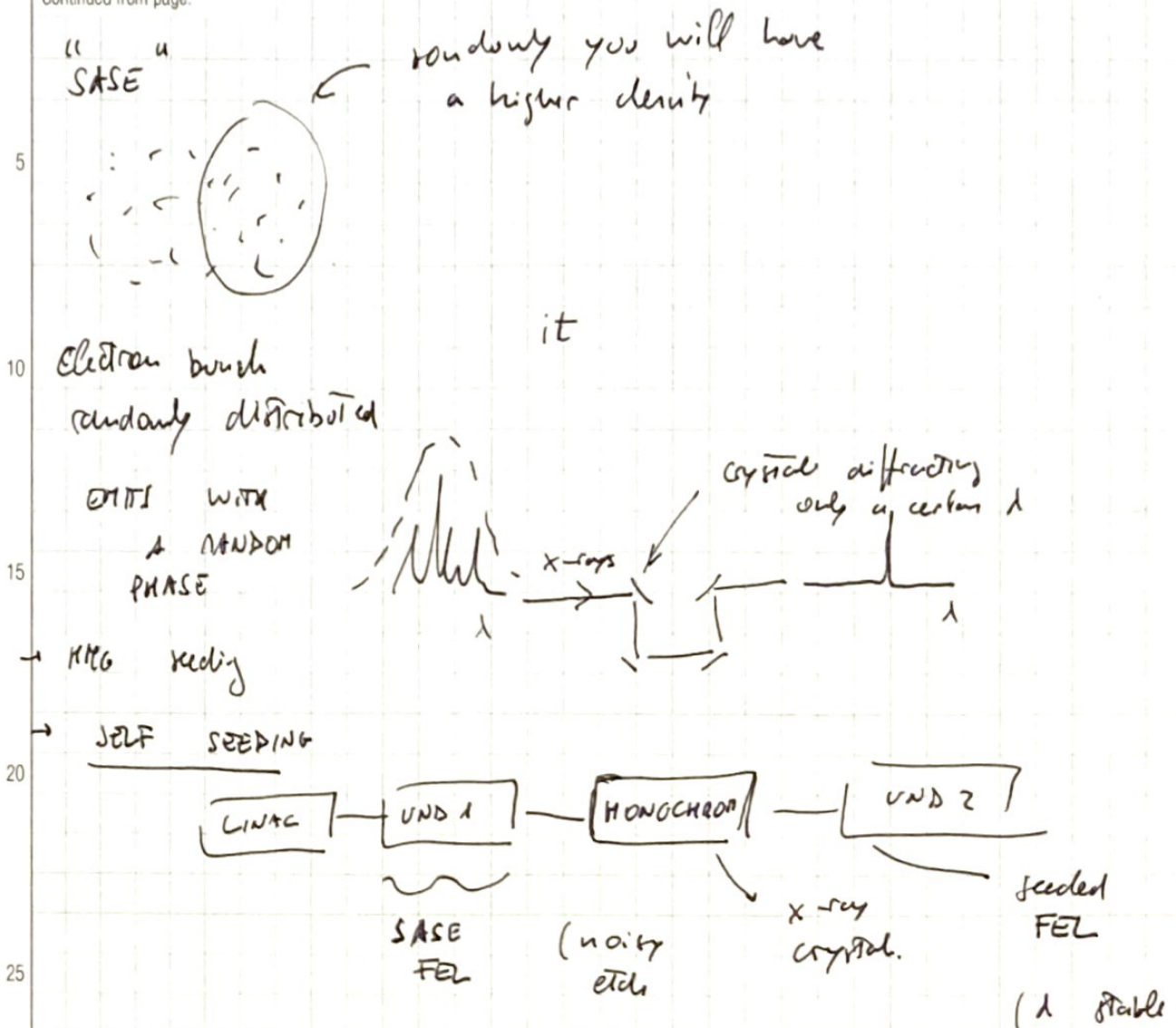
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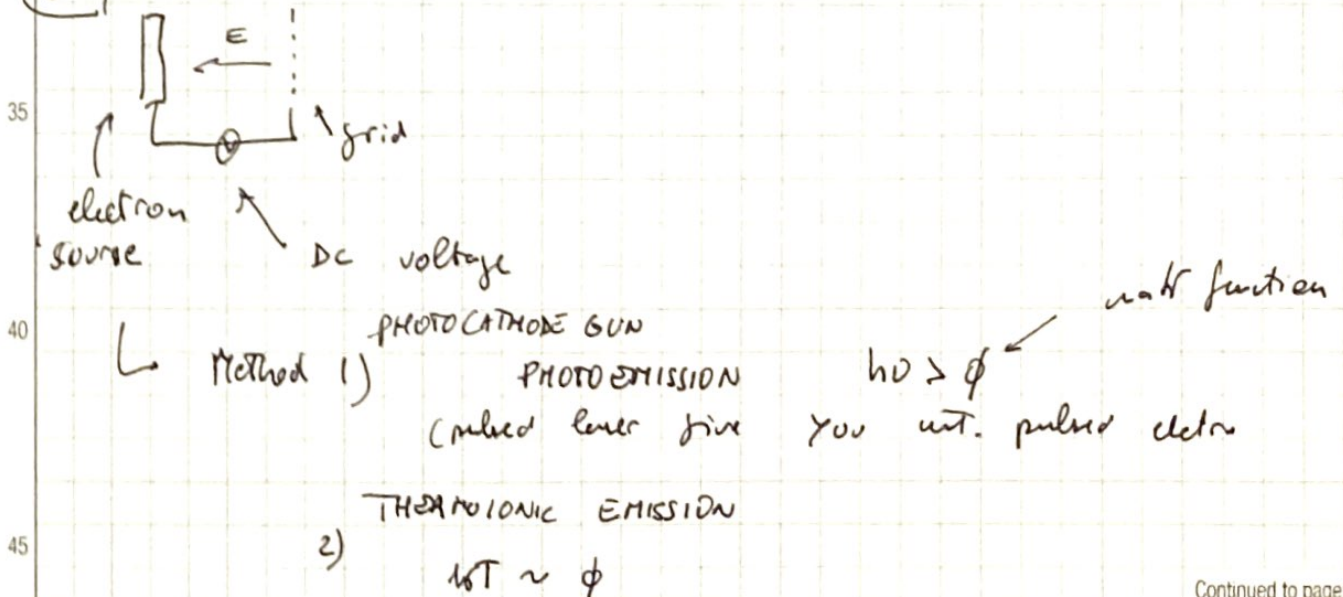
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How to make this relativistic e-beams??

ACCELERATOR TECHNOLOGY

GUN



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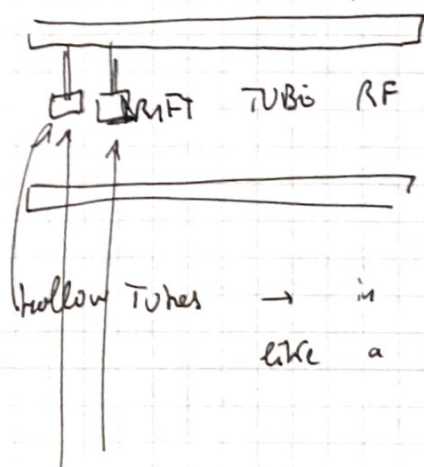
Voltage difference very large

naive 3 GeV voltage

idea: use
DC current. $\sim 1 \text{ MV}$ is the practical limit

static / quasi-static field limit.

RF cavities (on the side!)

Hollow Tubes $\rightarrow$ in this area
like a Faraday cage.

spacing and RF field are matched.

(you can change the length of individual drift tubes
to accommodate the acceleration)

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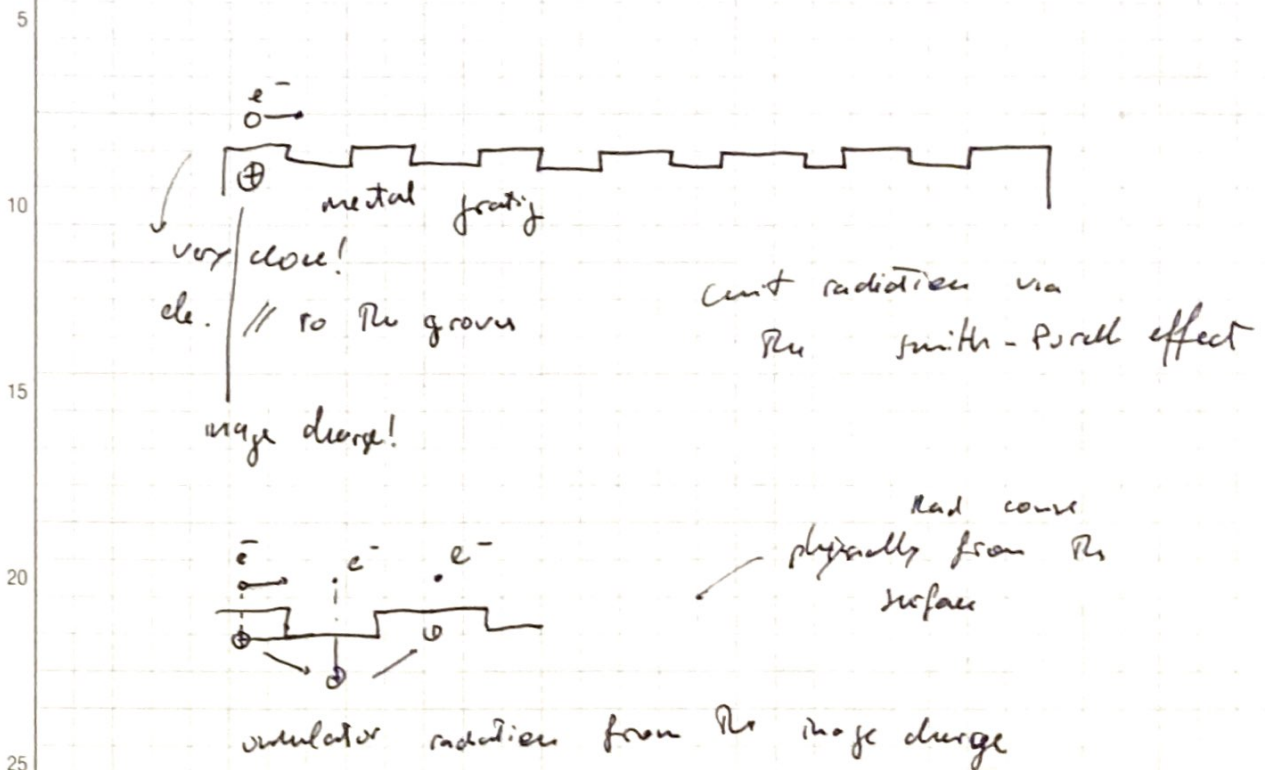
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Smith - Purcell effect.



You can also think about the Compton radiation here.

Use FEL as a pump. for laser.

GAIN has been demonstrated.

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23/11/23

Broca lectures as physics → printed slides

~~XXXX~~ → Overton
 → Noid prize

→ atomic unit of Time

$$\frac{\text{bohr radius}}{\text{velocity}} = 24 \text{ as} \rightarrow \text{Existence}$$

→ building an as laser

$$\Delta E \Delta V \sim 0.44$$

$$h\nu = 75 \text{ eV}$$

→ as laser bw

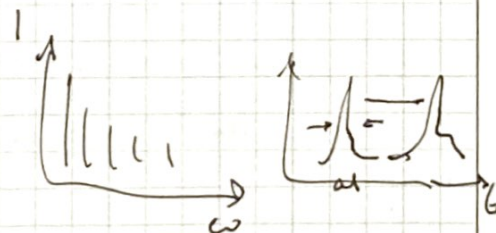
osc 1 eV filter 5 eV
 NLO

adding harmonics in phase

→ Review of 3-step model.

→ Trajectories + attodisp.

→ harmonic interfere → as pulses
 harmonic spectrum ← pulse interfere



pump - probe example → video break from
 wiki:

Ansys transfer + osci

How to isolate a single pulse spectrally

Continued to page:

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Technology

→ CEP examples.

→ CEP pulse velocity / group velocity

→ freq. comb CEP phase

→ $f - 2f$ interferometer

beatings

$$2f_n - f_{2n}$$

$$f_1 = n f_{rep} + \delta$$

$$f_2 = 2n f_{rep} + \delta$$

$$f_2 - 2f_1 = 2n f_{rep} - 2n f_{rep} + 2\delta - \delta$$

→ octave spanning oscillator

→ ultra quantum on stabilizing a laser

broadened in
a photonic
crystal fiber→ locking to the $n f_{rep}$ example

→ CEP "tagging" alternative

→ How to lock? piezo mirror
(not the most practical)

pump power modulation

CEP
Stable
pulses

→ 15 min break

→ few-cycle pulse

HCF 10^{12} W/cm^2 ← White light generation

IR → UV ~ 1 m fiber length.

→ broad spectrum but chirped

→ Chirped mirror compressor ~ 10-15 mirrors

→ question about higher order spatial modes of the fiber
rather to underfocus than to overfocus

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→ excites higher order
modes

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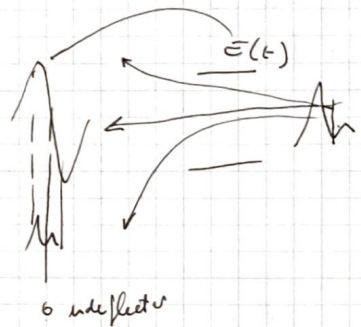
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→ metal or mirror filters

self-cycle cut-offs

→ measurement of attosecond pulses

examples -- here

streak camera → backward
couplerTime - space mapping on the screen
speed of $E(t)$ too slow

as. PHZ

as. STREAK CAMERA

IR E field + XUV as pulsesdon't ionize
'poke the electrons'

ionizes

give an additional momentum
analogytime → momentum
projection

$$\text{resolution } \Delta t = \frac{\Delta p}{eE_0}$$

Continued to page:

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→ Question world record? 43 ns

⇓

however very large error

→ Question as. ~~little~~ delays in photoemission

↳ answer "difference" in phase of emission

→ compensation of the attodisp achieved with metal filters

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23/11/23 ~~23/11/23~~~~23/11/23~~ → Carbone ←

as pulses of electron → quite hard due to repulsion

44) COHERENCE LECTURE

Exam format:

~15

Rookie → List of questions ~~are~~ available

11 prepared questions

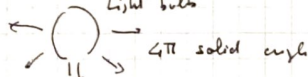
Jor: (20 min) 1 x random

→ blackboard

→ Rookie mistake ...

Light bulb

What is the difference?



Laser



Laser beam divergence dictated by diffraction

 $\theta \sim 10^{-4}$ rad. → solid angle $\frac{4\pi}{\pi \theta^2} \approx 10^8$ more directional than1W cw laser → still 10^2 intensity higher

60W cw lamp

I can also collect the lamp light and focus it
This is not a sufficient criterion

Brilliance

$$\text{Brilliance} = \frac{\text{Power}}{(\text{Surface}) \cdot (\text{solid angle})}$$

$$B = \frac{P}{S \cdot \Omega} \Rightarrow \text{It is a}$$

CONSERVED
QUANTITY

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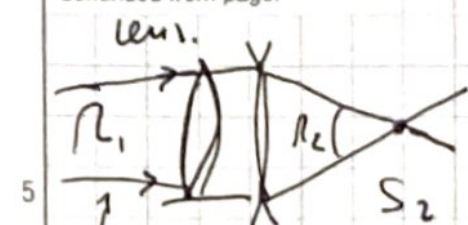
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very small S_1 very collimated S_2

$$B_1 = \frac{P}{S_1 \Omega_1}$$

$$B_2 = \frac{P_2}{S_2 \Omega_2}$$

S_2 smaller but Ω_2 much larger $\rightarrow$ ~~total~~ B conserved

THEOREM

Archimedes idea cannot have ever work
the PRINCIPLE OF THERMODYNAMICS

Inherently a much better brilliance

— COHERENCE

Temporal

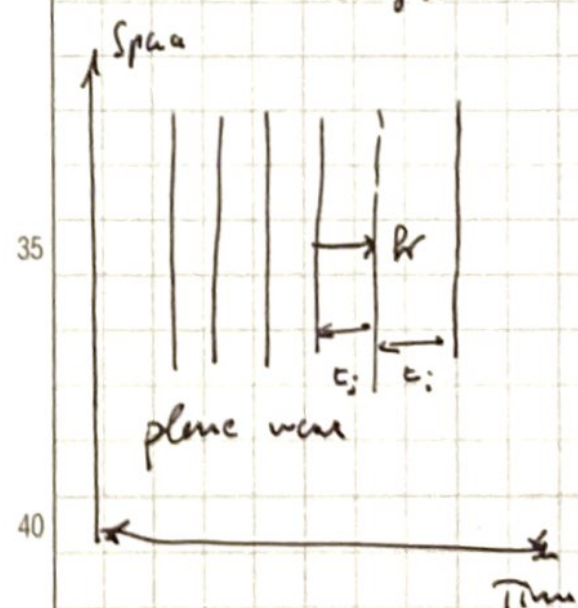
or /

Spatial

coherence

Temporal coherence length

Spatial coherence length



perfectly coherent

$\rightarrow$ points separate in space have the same phase

$\rightarrow$ all the t_i, t_j are the same

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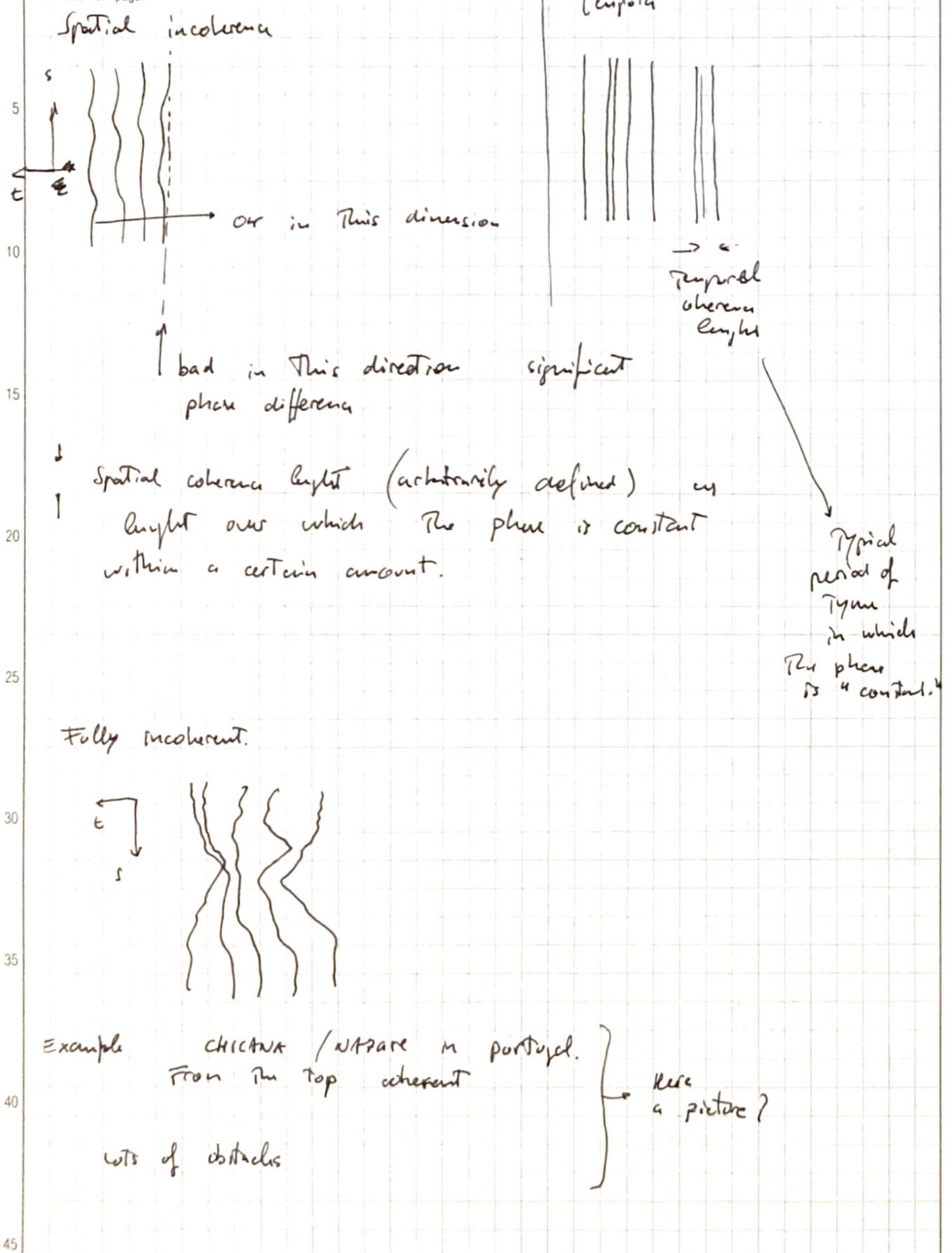
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Light bulb



amplitude
phase

A_A, ϕ_B

A_B, ϕ_B

For thermal light sources they are completely uncorrelated

→ Classical coherence Theory

→ Higher order coherence → quantum coherence

TEMPORAL COHERENCE

correlation functions

$$\langle f(t) f(t+\tau) \rangle$$

↪ average over possible t

$$= G(\tau)$$

Temporal autocorrelation

10^6 dice

vs

1 die

thrown 10^6 times

average
3.5

↪ defects/imperfection/non idealities.

can move a little bit
the mean

$$3.50001^{\circ}$$

At casino they change the machines!

ERGODIC HYPOTHESIS

assume that a test newent on
the a high source

$$G(\tau) = \langle E(t) E(t+\tau) \rangle$$

ERGODIC THEOREM

ice
ice

→ melt



water

phase transition

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atomic motion → order parameter

→ very
to
intermediate
region

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ERGODIC Theorem

intermediate states are all equally probable

(actually this is not TRUE)

OK in a macroscopic description → fails when doing a microscopic description

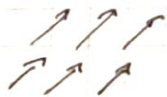
What if one intermediate is much more likely?



→ If you care only about final state and not intermediate state

→ You can have a metastable intermediate HIDDEN PHASE

Ferromagnetic system



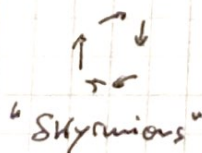
FERRO-



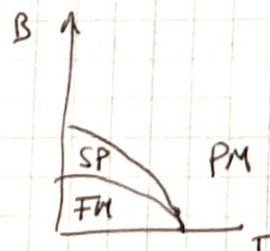
PARA- MAGNET

TOPOLOGICAL MAGNETS

SPIN VORTICES



"Skyrmions"



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adiabatically cooling / increase of B 

goes through equally probable intermediate state

you ~~change~~ change slowly B

short lived

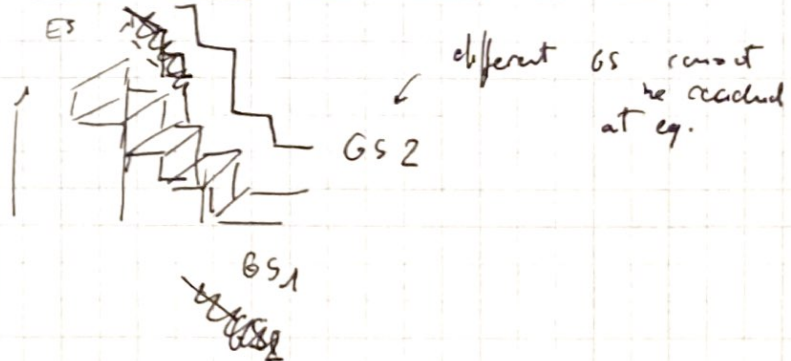
slow enough to ~~be~~ populate all the intermediate states for the same amount of time (= with the same probability)

- you can exit the system in a meta-stable fashion in the FM phase
- you cannot get it in an adiabatic way only possible through the

(reversible) HOPKINS EFFECT

~~PHYSICS TODAY~~ 2011

→ Double staircase example



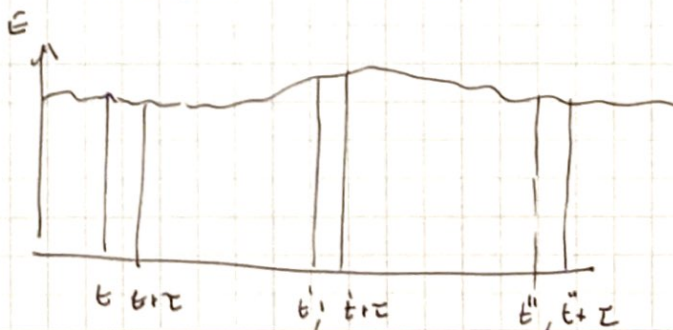
$$E(\vec{r}, t) = A(r) e^{i(\omega t + \vec{k} \cdot \vec{r} + \phi(\vec{r}, t))}$$

random function

complex conjugate

$$G_1(r, z)$$

$$G_1(r, z) = \langle E^*(\vec{r}, t) E(\vec{r}, t + z) \rangle$$



Assumption

→ The fluctuations are caused by an ergodic process

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Take the same source (laser) check what it does at different times (collect)

$$E^*(t_1) E(t_1 + \tau) + E(t_2) E(t_2 + \tau) + \dots$$

Number of samples

$$\frac{1}{T} \int_{-T/2}^{T/2} E^*(t) E(t + \tau) dt$$

$$G_1(\tau) = \lim_{T \rightarrow \infty} \frac{1}{T} \int_{-T/2}^{T/2} E^*(t) E(t + \tau) dt$$

neglect the spatial dependence

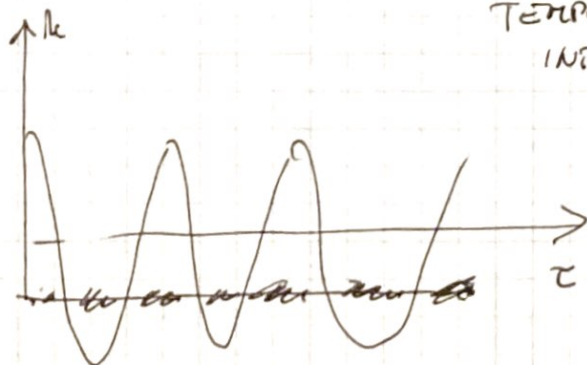
IMAGINE THAT A and ϕ are STATIONARY
(no fluctuations)

For a coherent source

do the integral

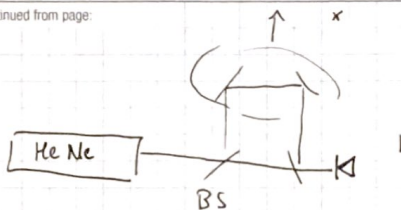
$$G_1(\tau) = A^2 \cos(\omega_0 \tau)$$

PERFECT
TEMPORAL
INTERFERENCE



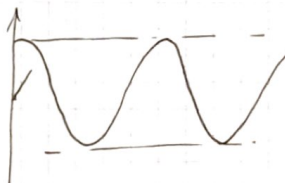
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Ryderson

For a perfect source G_1



For a real source this decays

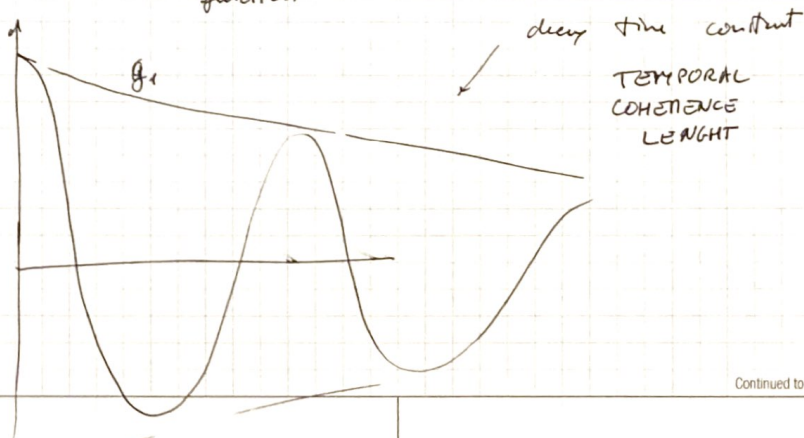
$$G_1(\tau) = \frac{\langle A^2 \rangle \langle A(t)A(t+\tau) \rangle e^{-i\omega\tau}}{\langle A^2 \rangle} = \langle A(t)A(t+\tau) \rangle e^{-i\omega\tau}$$

envelope function

$$G_1 = \langle A^2 \rangle e^{i\omega\tau} g_1(\tau)$$

$\nearrow 1$ coherent
 $\searrow 0$ incoherent

Temporal correlation function



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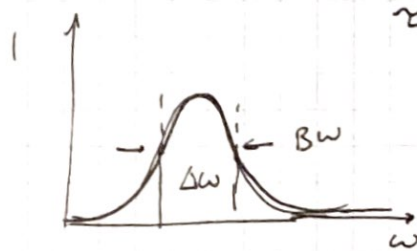
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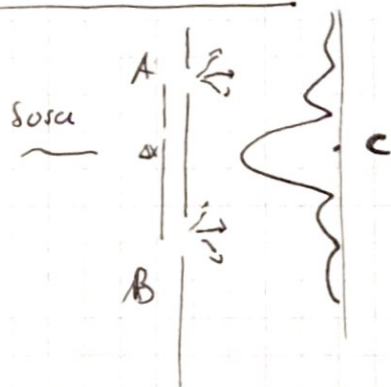
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~~scribbles~~YOU CAN DO THE SAME IN THE ω DOMAIN $E(\omega)$ 

$$\gamma_c \propto \frac{1}{\Delta \omega}$$

bandwidth of the source

SPATIAL COHERENCE

$$E_c = E(r_A, t) + E(r_B, t + \tau)$$

What happens when we put the slits further apart

→ Interference pattern disappears after a certain R_c coherent length

Note this is a statistical average!

HIGHER ORDER COHERENCE FUNCTION

n -th order
Take the correlation at n different points

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very ~~easy~~ generic.

$$G_n(x_1, \dots, x_n, x'_1, \dots, x'_n) = \langle E^*(x_1) \dots E^*(x_n) E(x'_1) \dots E(x'_n) \rangle$$

$$\vec{x} = x, y, z, t$$

this GLAUBER FUNCTION



$$|G_n| = \left[\prod_k G_2(x_k, x'_k) \prod_k G_1(x'_k, x_k) \right]^{1/2}$$

$$g_n = \frac{|G_n|}{\prod_k \langle I_n(x_k) \rangle \prod_k \langle I(x'_k) \rangle}$$

$$G_1(z) = \langle I \rangle e^{i\omega_0 z} \quad g_1(z) \quad \text{If you consider only 1}$$

$$|G(z)| = \langle I \rangle \Rightarrow g_1 = 1$$

for ~~the~~ higher orders? 2nd order correlation function we have already what we need to characterize the laser

$$\text{ASSUME } x = x' \quad x = x, y, z, t$$

same coordinate but @ the second order level

$$G_n = \langle I(x) I(x_n) \rangle$$

intensity correlation between different points in space

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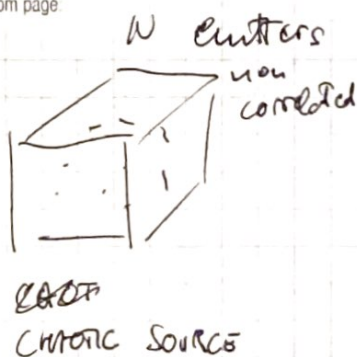
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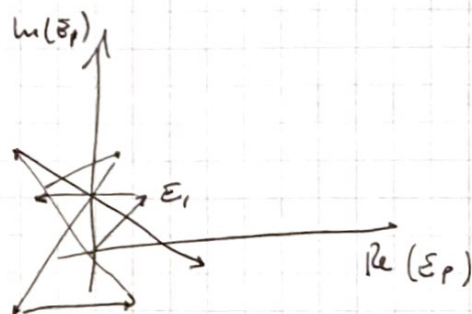
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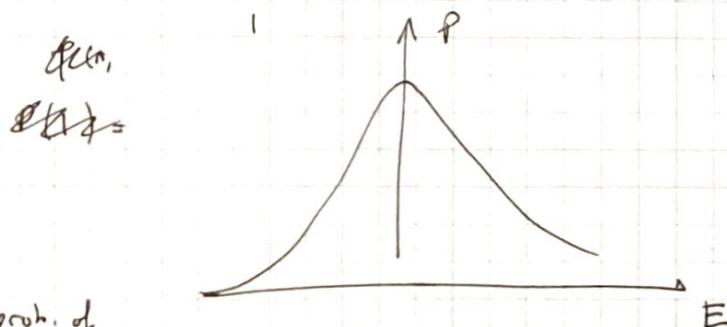


$$E_p = \sum_{k=1}^N E_k(t)$$



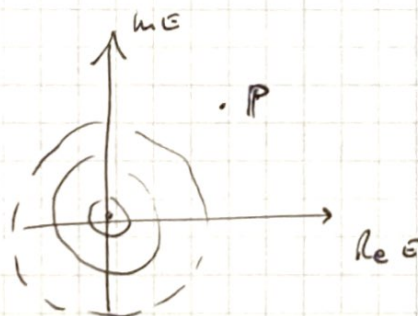
RANDOM WALK

Ask "What is the probability of having a certain field intensity at a point P "



prob. of
having field E

$$W(E) = \frac{1}{\langle I \rangle} e^{-\frac{|E|^2}{\langle I \rangle}}$$



most of the interference is destructive

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sun
terrible temporal coherence
fs

eye 200 ns
average over
 $\sim 10^{12}$

Example of the SPOTLIGHT with the laser

What we see is mostly darkness

5/12/23

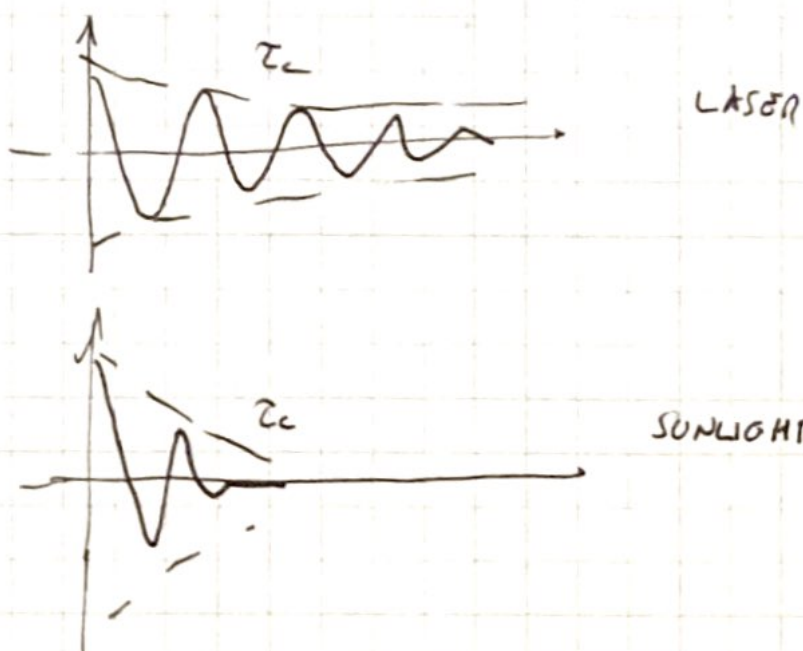
order parameter $\rightarrow$ transition to a different type of light

$\rightarrow$ movie about vision with a speckle pattern with a "faster" detector.

$$G_1(\tau) = N \langle I \rangle e^{-\tau/\tau_c}$$

N counts

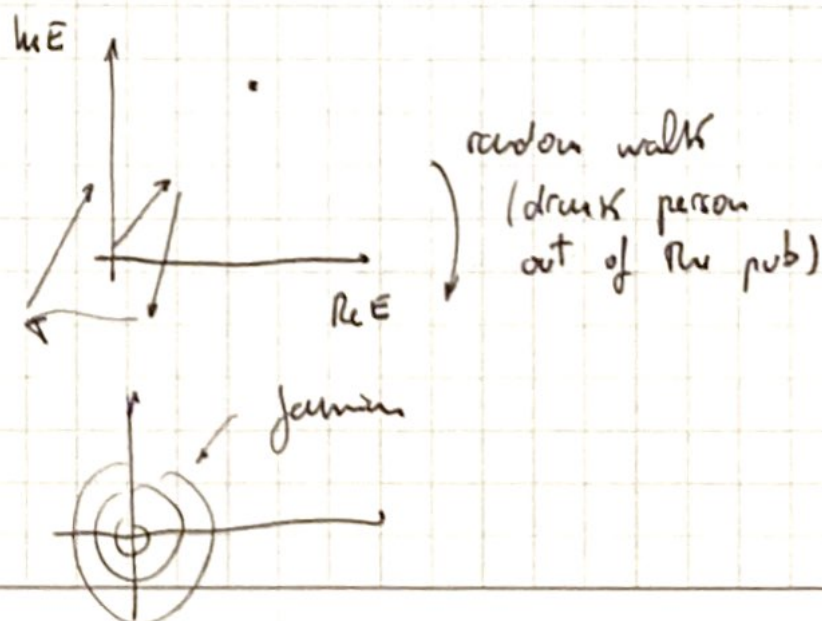
First order corr.
function



Second order corr. function

$$G_2(\tau) = N^2 \{ \langle I \rangle^2 + |G_1(\tau)|^2 \}$$

TRUE ONLY FOR RANDOM PROCESSES
(Gaussian distribution for a random walk)



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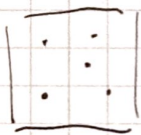
What are the consequences? This apply for many fields

Quantum computing: True random sequence of numbers are difficult to generate

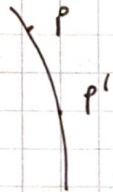
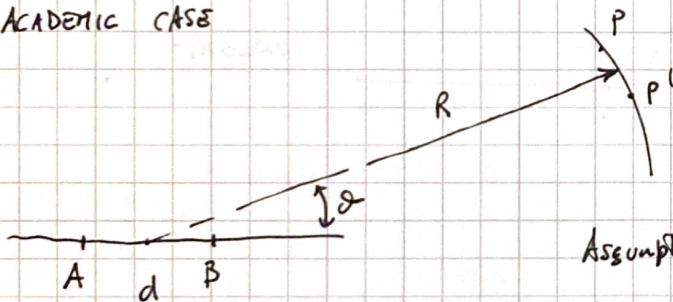
→ Few processes are truly random?

LAVA LAMP.

of balls at a certain given time is a truly random number

SPATIAL COHERENCE

Box with atoms

phase relationship between P and P' ACADEMIC CASEAssumption $R \gg d$

phase difference

$$\Delta\phi = \frac{2\pi}{\lambda} \cdot [(BP - AP) + (BP' - AP')]$$

Two emitters
distance d
between each
other

$$\Delta\phi = \frac{\lambda R}{2d \sin \theta}$$

IMPOSING THAT $\Delta\phi = \pi$: assume that a source is coherent

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Coherence radius: $R_c \sim \frac{\lambda R}{d}$

5 Transvers coherence for a caotic source inversely proportional to R_c fix of the source (d)

10 only way to make it coherent is to reduce to a single caotic emitter (low flux)

→ It increases with distance

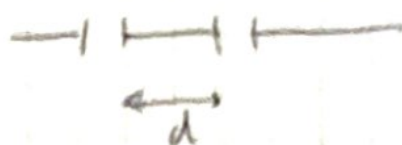
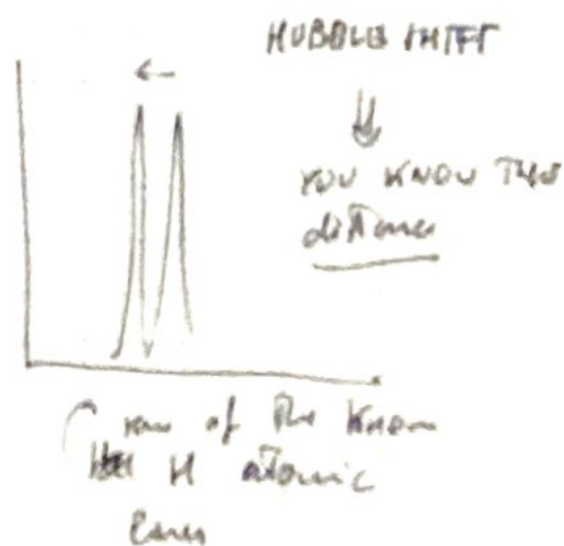
15 APPLICATION:
astronomical problem

o star.

- exploit the optical coherent
- star is a caotic source with a very good approximation
- λ_{star} known

observer on earth

What is R_c like?



2x apertures with a variable distance

→ increase until the interference disappear. $\Rightarrow$ you measure R_c

$$R_c \sim \frac{\lambda R}{d}$$

For the sun

$$d = \frac{150}{10^6} \cdot 10^6 \text{ km}$$

$$\lambda = 0.5 \text{ nm}$$

$$R_c \sim 50 \mu\text{m} \Rightarrow d = \frac{1.6}{10^6} \cdot 10^6 \text{ km}$$

1.6

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Lamp vs Laser

SPATIAL COHERENCE

chaotic source

$$R_c \sim \frac{\lambda R}{d}$$

There
is a relationship
between R_c and d

NOT TRUE FOR A LASER

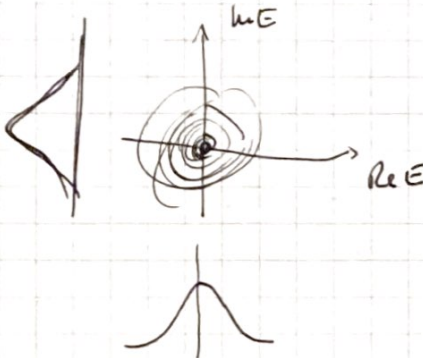
Laser beam is fully coherent ^{throughout} its ~~entire~~ spot size



formula does not
hold for laser
since not
chaotic

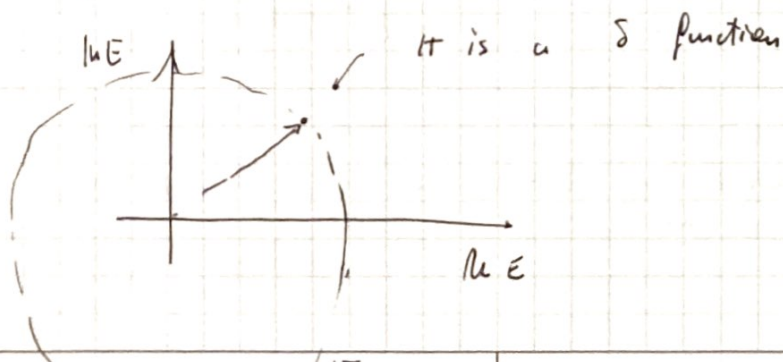
TEMPORAL COHERENCE

Chaotic source



FOR THE LASER

Feedback mechanism which forces the intensity to be
well defined amplitude.



Phase-wise can be anywhere

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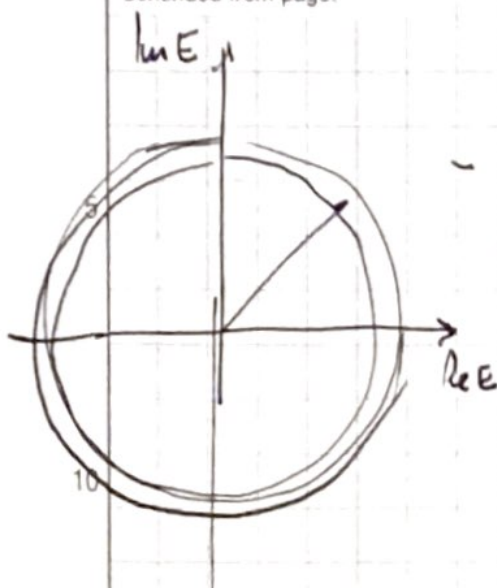
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- It is a RING at a given distance

2nd order phase transition between chaotic to laser light.

ELECTRON SOURCES

- How to design an electron beamline?
- How to generate an electron beam?

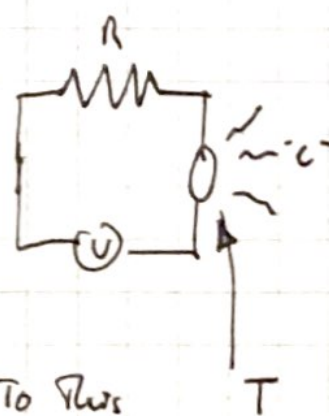
FEL
TEM

Article: NIMA Mancini et al. 2012
Nuclear instruments and methods

Sources of electrons

Thermionic emitter

* Chaotic (Thermal processes)



a T is associated to this

→ ~~Blackbody~~ Blackbody radiation - To be able to define a Temperature
? .. equilibrium .. adiabatic .. ⇒ gaussian statistics



coherence lengths

$$\lambda_c \sim 1/a$$

$$\lambda_c \sim 1/\omega$$

bandwidth

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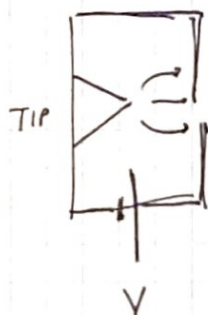
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FIELD EMISSION GUN



EXTRACTION FIELD

work function lowers at the tip..?

→ DIRECTLY COLLIMATED

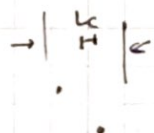
GOOD BRIGHTNESS

→ GOOD COHERENCE PROPERTIES

ALSO HERE THE T_c AND L_c ARE THE SAME → YOU CAN DECREASE THE SIZE

FOR CHARGED SOURCES COHERENCE IS A "KNOB"

→ increase the size of the beam

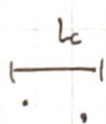
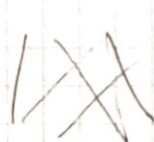


large beam with a small coherence length

↓
NO effects

2x scatterers

↙ throw away many electrons



larger beam

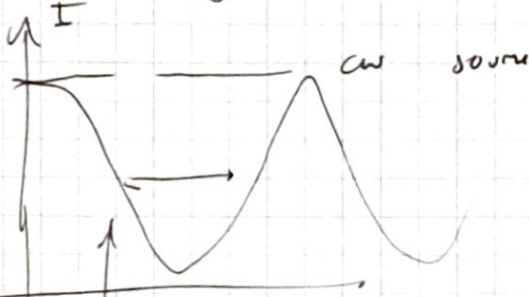
Here we see the interference effects between the scatterers

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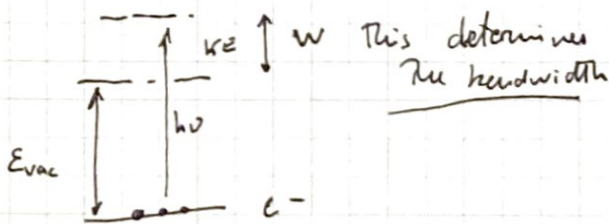
Electron lenses can be turned

Time varying current in a TIP

if ω photons are fs $\Rightarrow$ fs electron pulses

Still an incoherent source

$$R_c = \frac{1}{d}$$

- e^- are fermions- ~~the~~ coulomb repulsion

The pulse spread.

Low Landau / Einstein

$$\tau_c \sim \frac{1}{\Delta\omega}$$

$$\Delta\omega \sim E \sim \frac{kT}{\hbar}$$

The higher the T the higher

note that you can have
a cold field emission
gun (100s K)

Thermionic 1000s

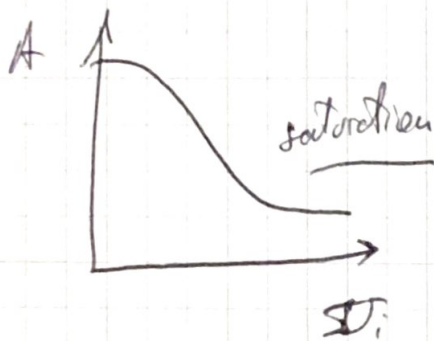
ultracold atom source $\rightarrow$ cool down to
few K

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 βA has to be conserved. $\rightarrow$ if $\beta A = 1$ bandwidth $\rightarrow 0$
 $G \rightarrow \infty$ } δ function

arbitrarily low

if $\beta A > 1$ above the threshold $\rightarrow$ infinite signal.

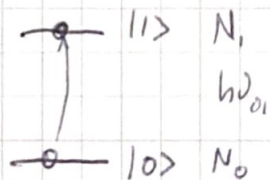
ingredients for the oscillator

① amplifier $\rightarrow$ Doppler.② retroaction $\rightarrow$ cavity.

generate radiation (photons)

accelerate charges $\rightarrow$ Bremsstrahlung
 $\rightarrow$ synchrotron radiation
 $\rightarrow$ dipole transitions

absorption



spontaneous emission

isotropic process
fluorescence

$$\frac{dN_1}{dt} = \sigma_{01}(\nu) \phi N_0$$

$\downarrow$ flux
abs. x-section

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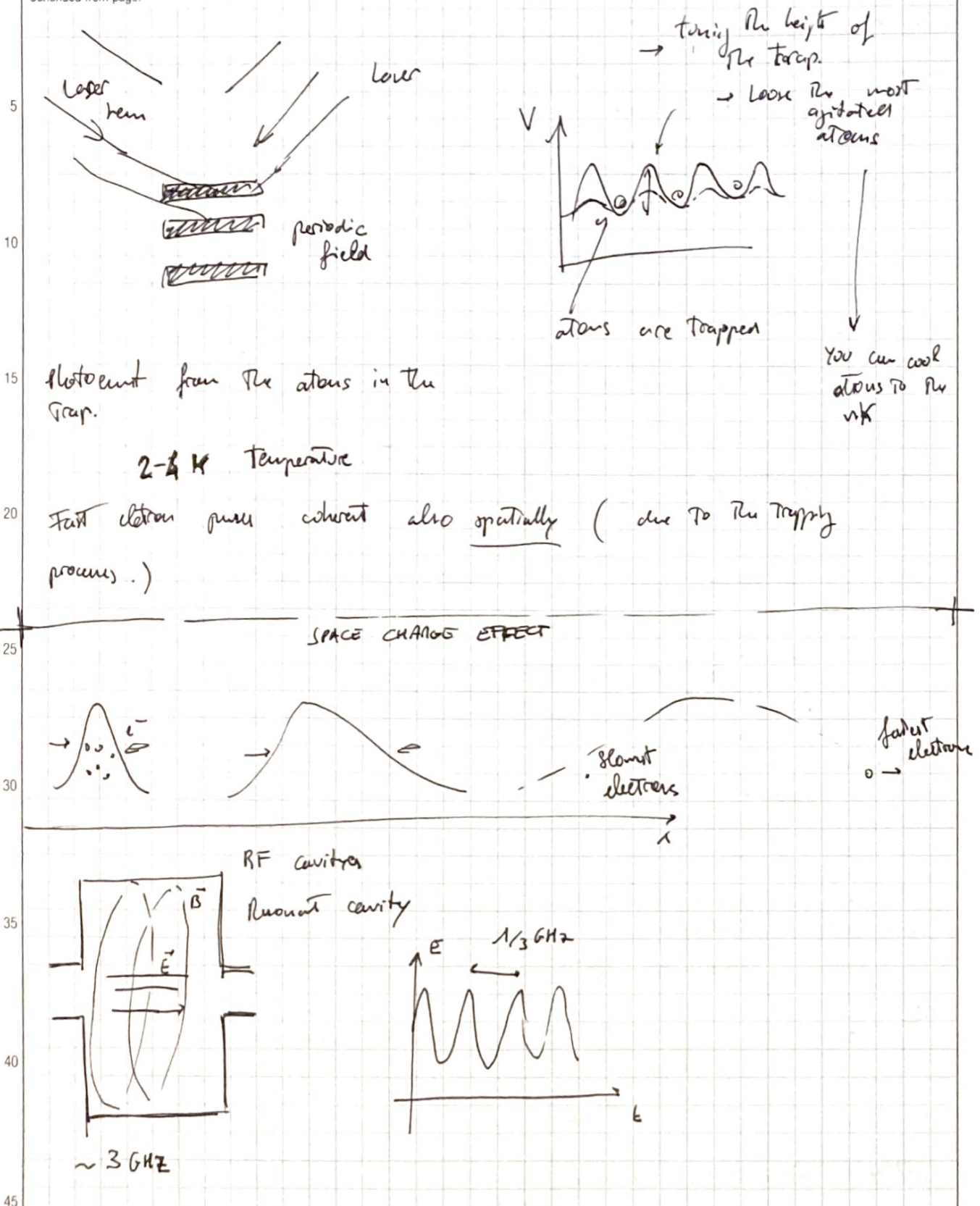
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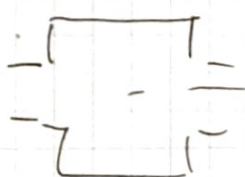
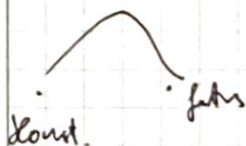
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o Synchronize the field to the laser

o You want a sign flip. when the τ pulse is in the center of the cavity

o The field accelerates the ~~electrons~~^{lowest} and slows the fastest electrons



TEMPORAL
FOCAL
LENGTH

$\downarrow$ (RF power
current, etc...)

→ other ingredient.

SPATIAL LENS FOR ELECTRONS

SOLENOID

windings



(Excursion δ on the ferrofluid.)

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→ CIB
→ Ultra-thin plate

20
2 demand
~20 demands

Lecture 14/12/23

Surface plasmon polaritons

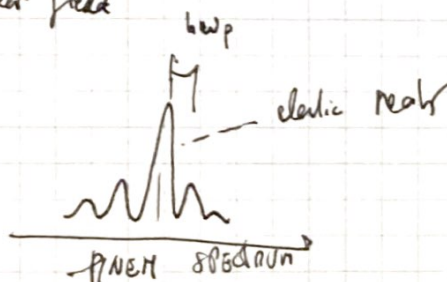
Drexel "edge of solids" ← suggested reading

Experiment of plasmon (a bit failed)

→ Plasmon resonance - SPR

↓
Trap light in the near field
in the JEM

- nanowires



Lorenzen et al., Nat. Comm. 7 13156 (2016)

Liatig 6 6407 (2015)

Vanacore 2018

→ Coherent control of plasmon resonance

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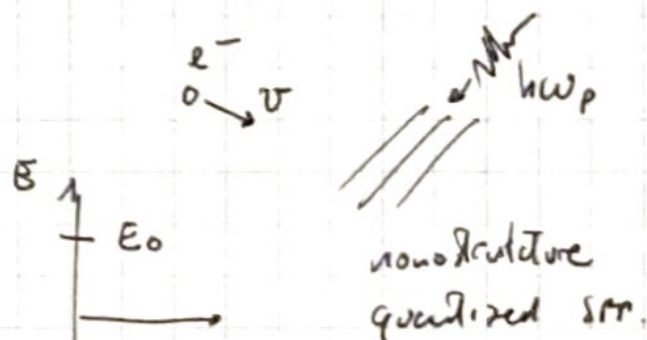
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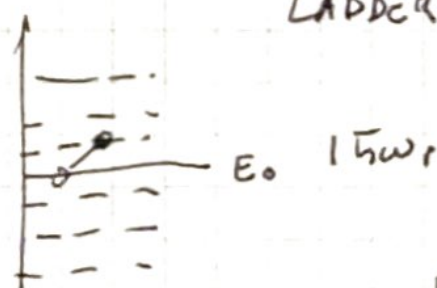
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- This was not done with an as. electron pulse
Trick of coherent control of E_0 to measure the ~~field~~ plasma field carrier
with as. resolution

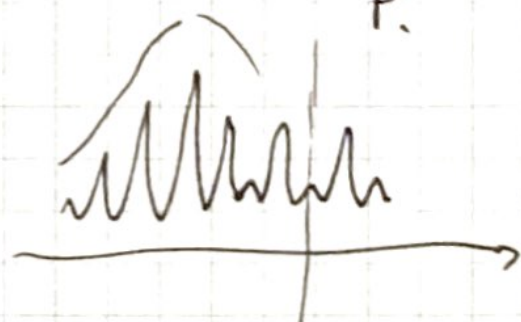
→ Initially in the e^- pulses there is 1 e^- only



SPLIT IN A QUANTUM
LADDER (inf. spaced)



Electron can jump in various
ways
2x up 1x down
→ probability of each process
is modulate by quantum
interference

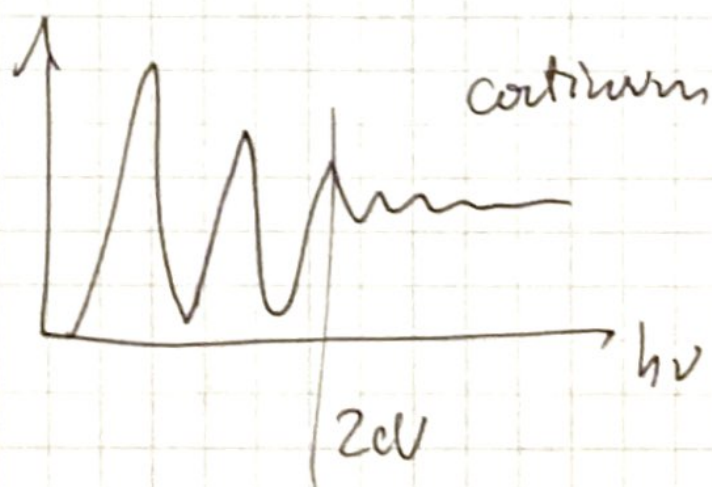


RABI OSCILLATIONS OF A QUANTUM SYSTEMS

Fert Nat. 521 4963 (2015)

Farb NJP 12 123028 (2010)

Jarvis de Abajo Nano Lett. 10 1859 (2010)



spectrum of
SPP.

Asked about Rabi - off resonance -

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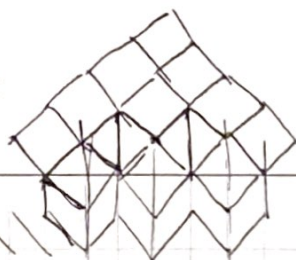
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5 Echtenkamp. not Phys.

10 As. electron pulses for 4D diffraction and microscopy
Bauer + Zewail

15 PONDONOVUS FORCE

20 An electron walks in a q. bar.

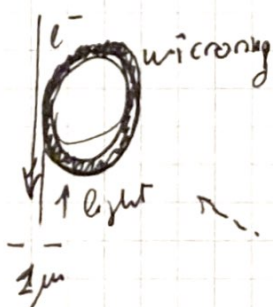
Dahm Science 373

(Kaminer)

25 Integrated photonic circuits

before int. length was

50 nm



Here is 10^6 more int. length

35 You can get the effect in CW

the rest

Kaminer did a similar exp.

high intensity laser light

→ treated chemically at high intensity

+

→ Thermal source

Due to cavity
Feedback!
check the other
lecture

the noise
needs to be

described quantum-mechanically

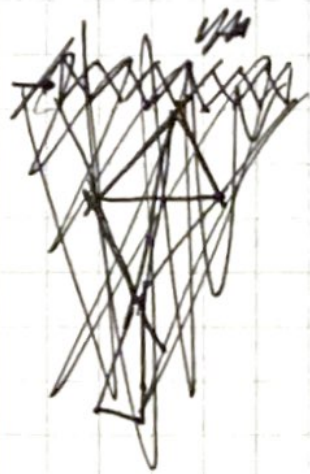
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- Coherent light → QUANTUM LADDER + RABI OSCILLATIONS

Thermal → fermion distribution

→ Only known light-electron entanglement



Disturbance description of phot. electric effect



bands.

best semiclassical description

Drude metal
(here need quantum plots)

Lamb-Sally paper

photoelectric effect without quantum light

laden Science Advances 6
Lopez comment

Quantum holography

Baum
2x
paper

Bob

~~Henrietta~~

Rorimoto

and

Nubbans

with Train of as pulses

Vanacore 2018 → septadecad control?

Proposed at FBL

Modulation of transverse components of the wavefunction

Vanacore Nat. Mat.

Neutron vortex beam

Few ideas for γ -ray lenses.

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w.ki

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