Theory of Quantum FEL and the QFEL Project

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Outline

1. Steady State and Superradiant instability
2. Classical SASE
3. Quantum FEL Model (QFEL) and Classical Limit
4. Quantum Linear Analysis
5. Quantum SASE: quantum “purification” and discrete lines
6. LENS experiment: BEC = QFEL
7. QFEL Project

R. B., N. Piovella, G.R.M. Robb, NIM A 543 (2005) 645 and ref. therein

Some references

HIGH-GAIN AND SASE FEL with “UNIVERSAL SCALING”

Classical Theory

(1) R.B, C. Pellegrini and L. Narducci, Opt. Commun. 50, 373 (1984).
(2) R.B, B.W. McNeil, and P. Pierini PRA 40, 4467 (1989)
(3) R.B, L. De Salvo, P.Pierini, N.Piovella, C. Pellegrini, PRL 73, 70 (1994).
(4, 5) R.B. et al,Physics of High Gain FEL and Superradiance, La Rivista del Nuovo Cimento vol. 13. n. 9 (1990) e vol. 15 n.11 (1992)

QUANTUM THEORY

(6) R. B., N. Piovella, G.R.M.Robb, and M.M.Cola, Europhysics Letters, 69, (2005) 55 .
(7) R.B., N. Piovella, G.R.M. Robb, Quantum Theory of SASE-FEL, NIM A 543, 645 (2005), and proc. FEL Conf. 2005
(8) R. B., N. Piovella, G.R.M.Robb, and M.M.Cola, Optics Commun. 252, 381 (2005)

See also

(9) F.T.Arecchi, R. Bonifacio, “MB equation”, IEEE Quantum Electron., 1 (1965) 169

Classical model with "Universal" Scaling

no free parameters

A: scattered field

"Collective FEL parameter"

R. B, C. Pellegrini and L. Narducci,
Opt. Commun. 50, 373 (1984).

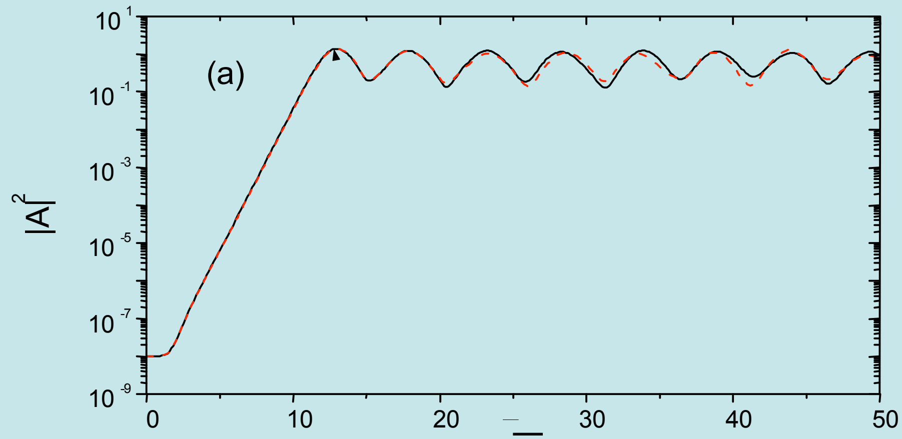
Position

Momentum

Steady State (S.S.) model

Steady State instability (with universal scaling)

R. B, C. Pellegrini and L. Narducci,
Opt. Commun. 50, 373 (1984).



“Collective FEL parameter”

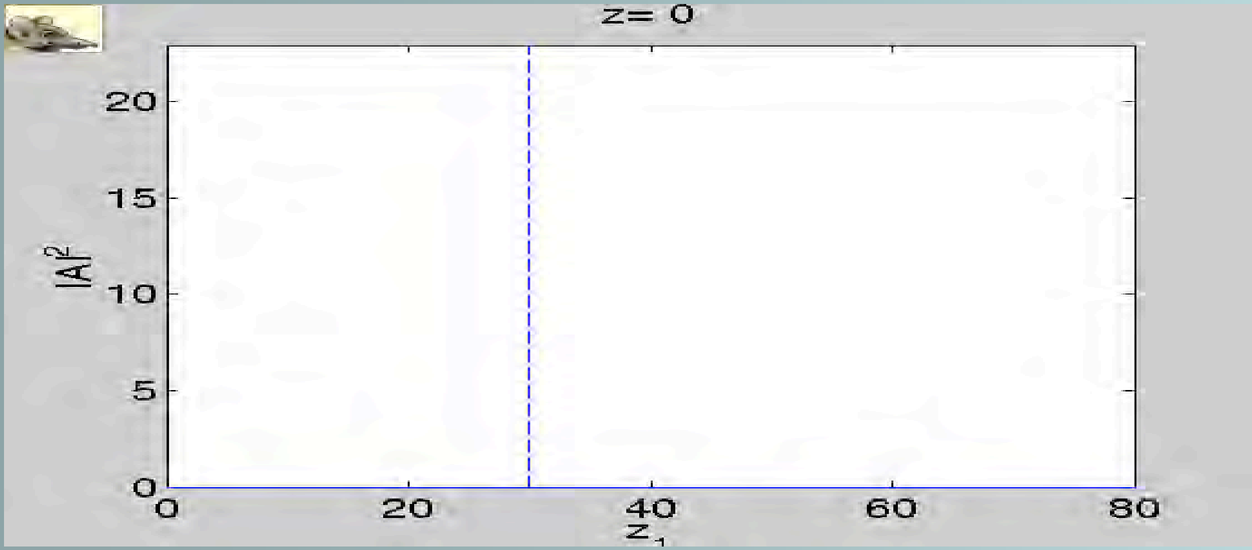
Exponential growth up to |A| ~ 1
Independently on the initial value

Possibility of
start up from noise.

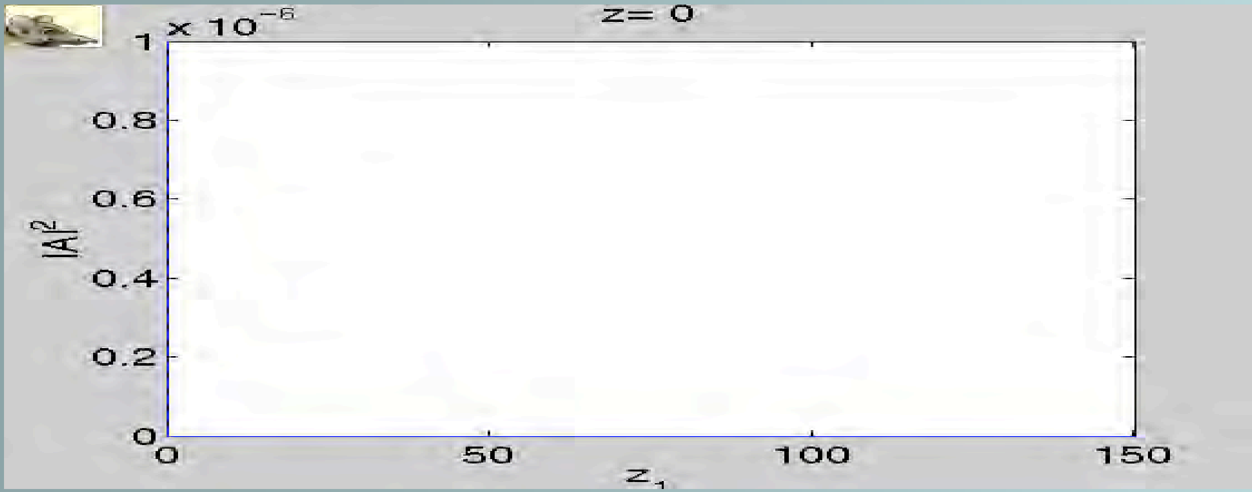
STEADY STATE AND SUPERRADIANT INSTABILITY,

Long and Short Bunch (uniform seed)

Evolution of radiation time structure in the electron rest frame



Strong SR



Weak SR

R. Bonifacio, B.W. McNeil, and P. Pierini PRA 40, 4467 (1989)

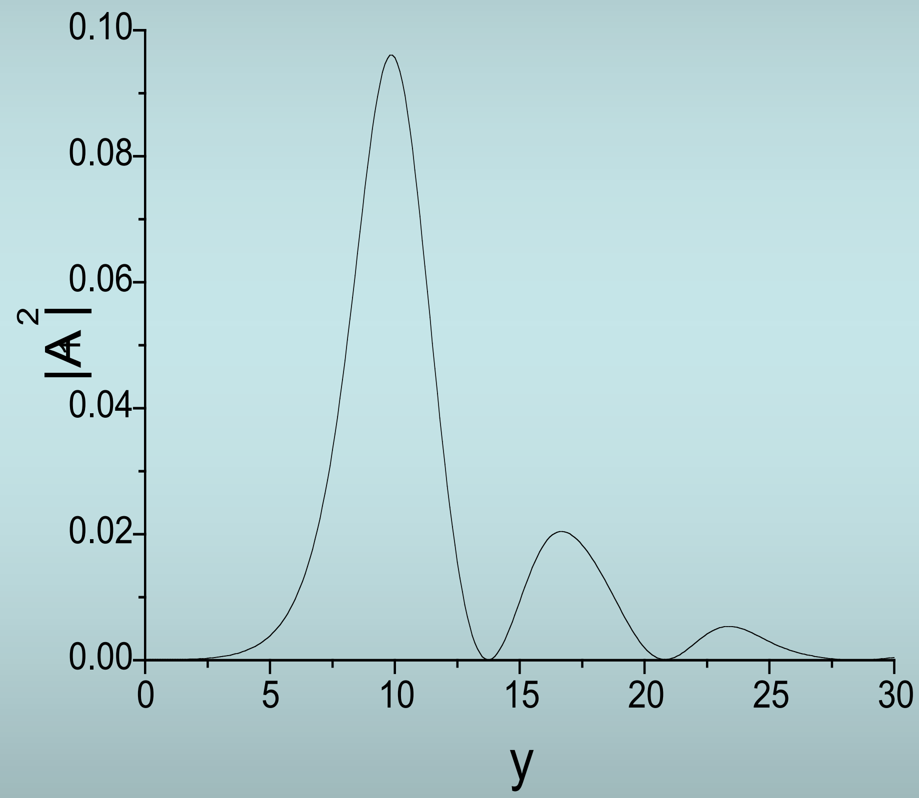
Soliton-Like solution and Superradiant Regime

(ref. 2,4)

CLASSICAL REGIME:

width

SUPERRADIANCE

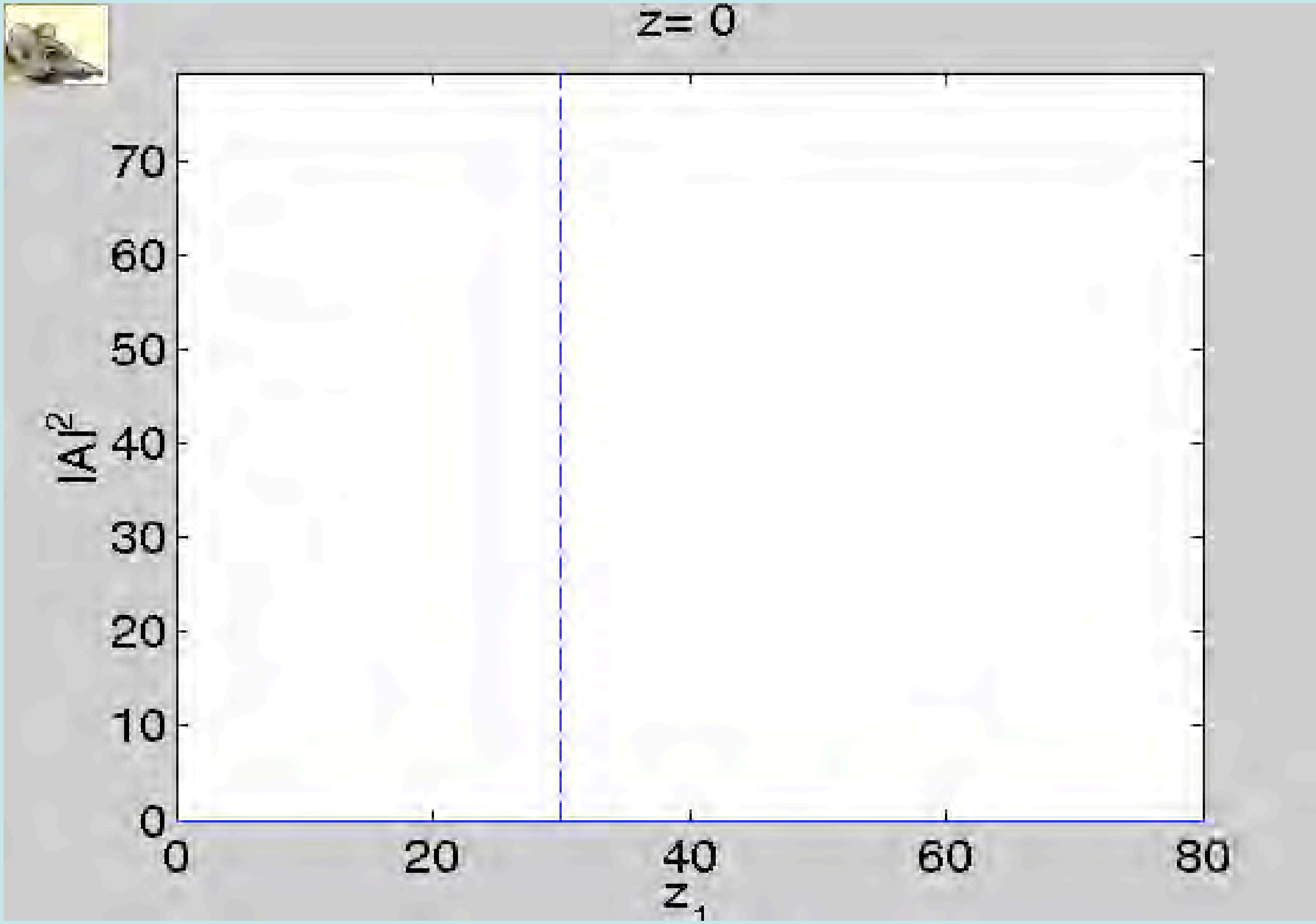


SELF SIMILAR SOLUTION

SUPERRADIANT INSTABILITY,
(uniform seed) $L=30L_C$, detuned ($\delta=2$)

R. Bonifacio, B.W. McNeil, and P. Pierini
PRA 40, 4467 (1989)

Evolution of radiation time structure in the electron rest frame



No steady state Instability

SR does not depend on detuning and does not saturate

Classical SASE

Ingredients:

i) Start up from noise

ii) Propagation effects (slippage)

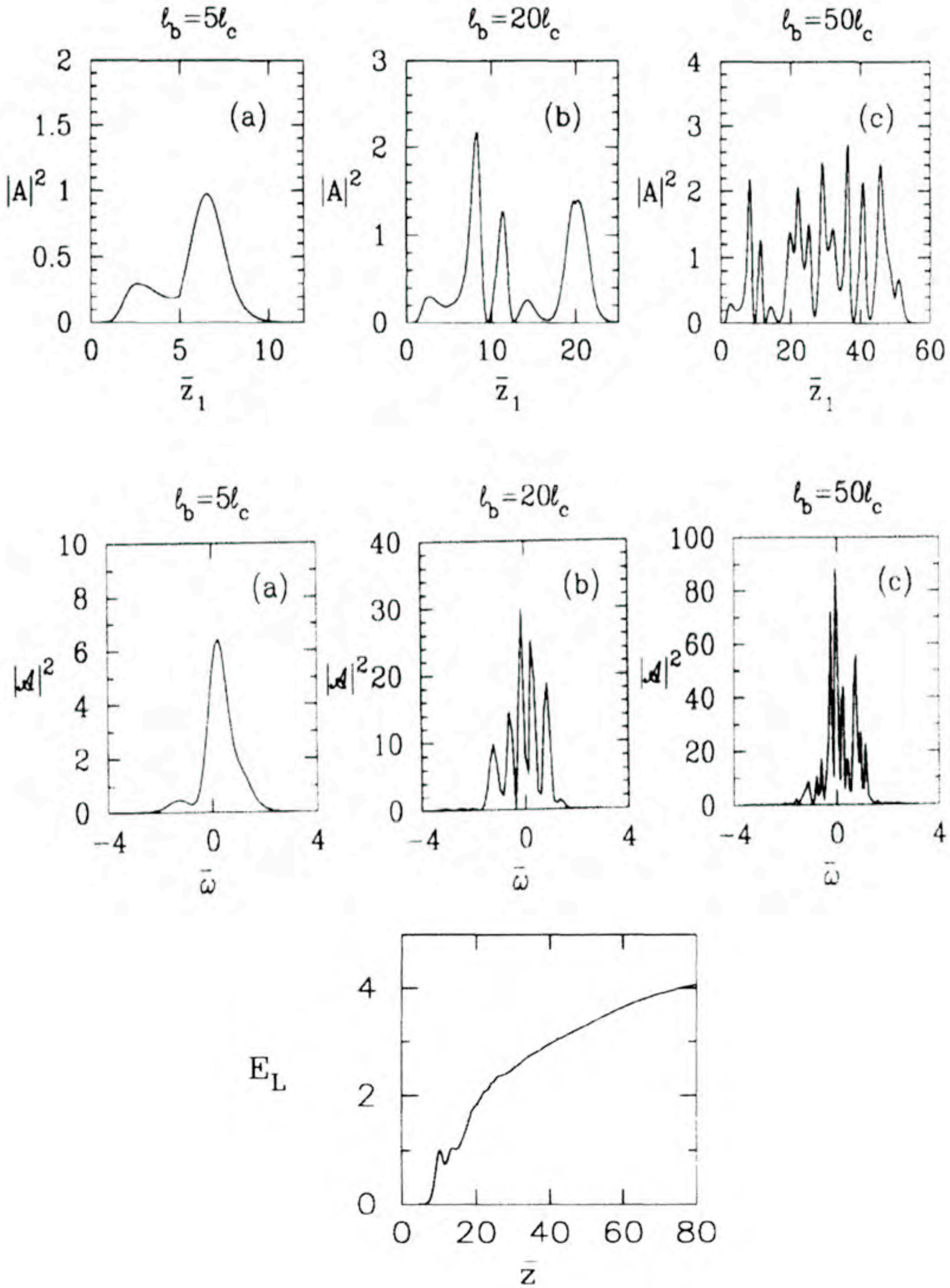
iii) Superradiant instability: (no steady state instability)

Self Amplified Superradiant Emission

(RB, L. De Salvo, P.Pierini, N.Piovella, C. Pellegrini, PRL 73 (1994) 70)

⇓

The electron bunch behaves as if each cooperation length would radiate independently a weak SR spike which gets amplified propagating on the other electrons with no saturation. Spiky time structure and spectrum.



CLASSICAL SASE

reprinted from PRL 73 (1994) 70

Time structure:

Almost chaotic behavior:

number of random spikes goes like .

Spectrum:

is just the envelope of a series of narrow random spikes

If a single SR spike.

At short wavelengths => many random spikes.

Total energy does not saturate (at 1.4).

Canonical Quantization

Quantization

The QFEL model for the matter wave

Derived from Q-field theory by G. Preparata (Phys. Rev. A, 38 (1988), 233)

QFEL (BEC) propagation model (ref.8)

matter wave (as in a BEC)

QFEL
parameter

R. B., N. Piovella, G.R.M. Robb,, NIM A 543 (2005) 645
and proc. FEL Conf. 2005 (Stanford)

; Q. F. T. by G. Preparata† (Phys. Rev. A, 38 (1988), 233)

Classical Limit: $\hbar$

One can prove that the Schroedinger equation for the QFEL model reduces to the classical Vlasov Equation for the Quantum Wigner function in the limit:

$\hbar$

In the classical limit, with universal scaling, no dependence on $\hbar$

(Ref. 6, 8)

Classical limit when (ref.6,8)

Wigner function

Classical Vlasov Equation

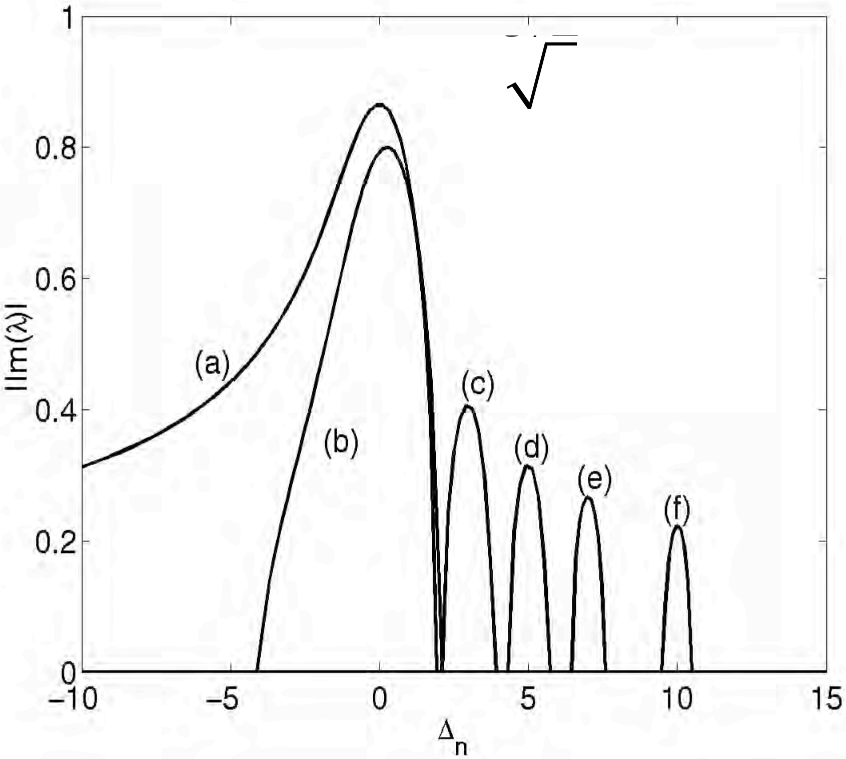
The Momentum Representation (ref. 7, 8)

is the probability that an electron has a momentum

QFEL "working equations"

Linear Theory: QM

As if classical rect. dist.

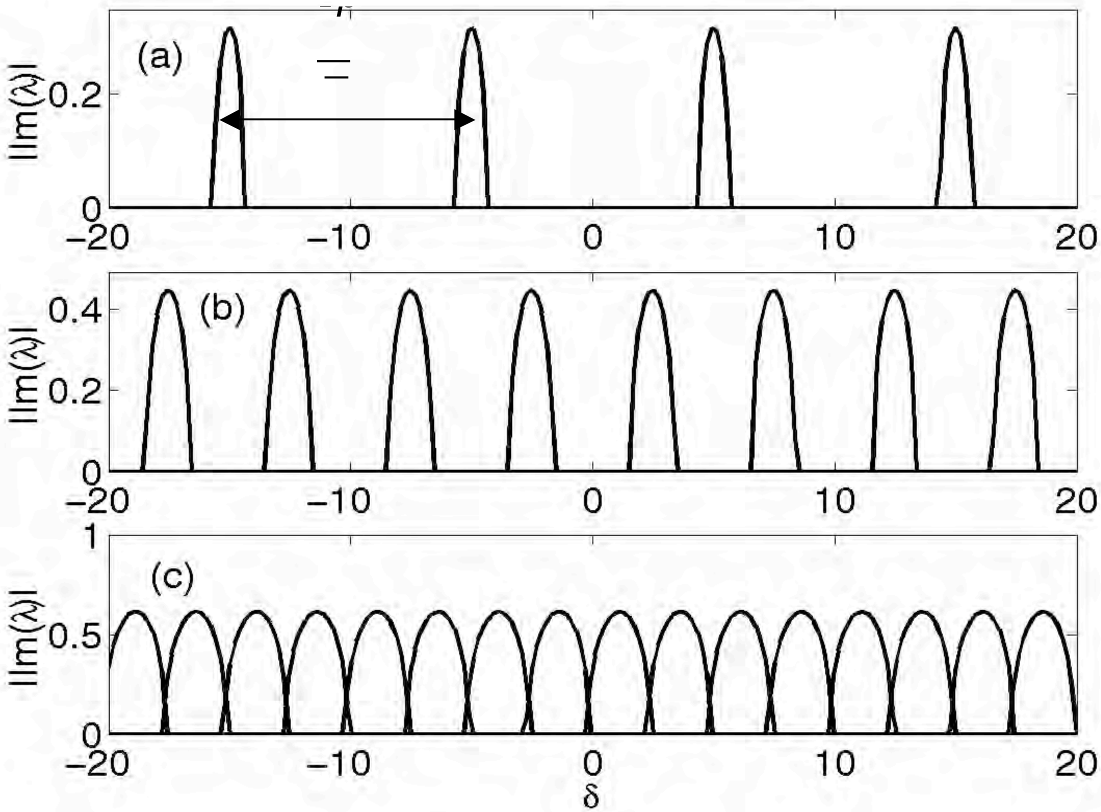


Classical limit (a) (ref. 1)

Quantum regime

(ref. 7, 8)

The Discrete frequencies as in a cavity

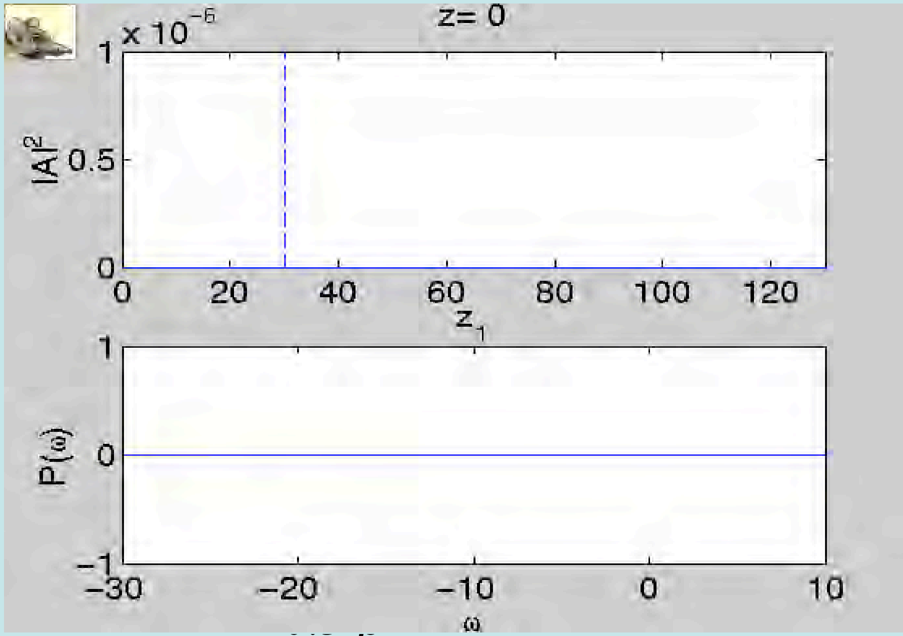


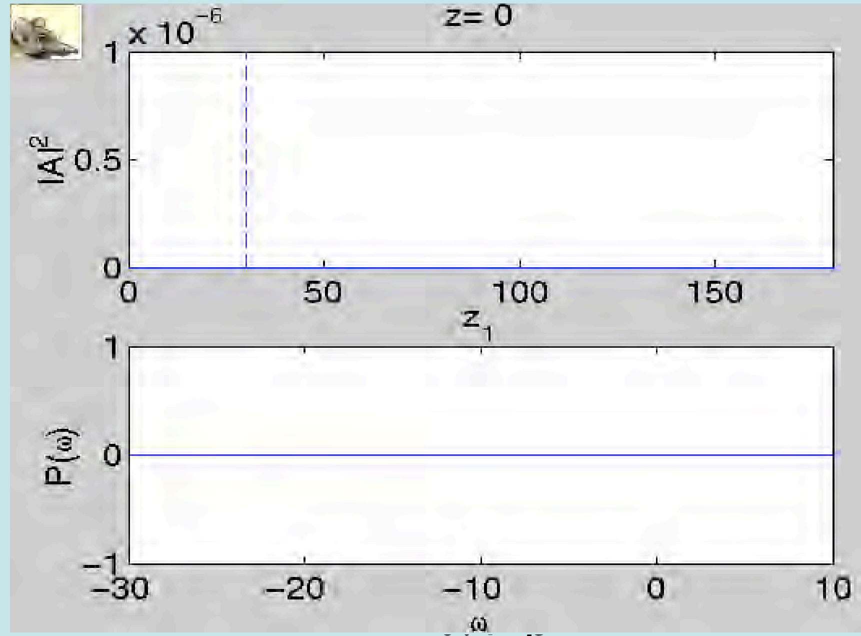
Frequency separation

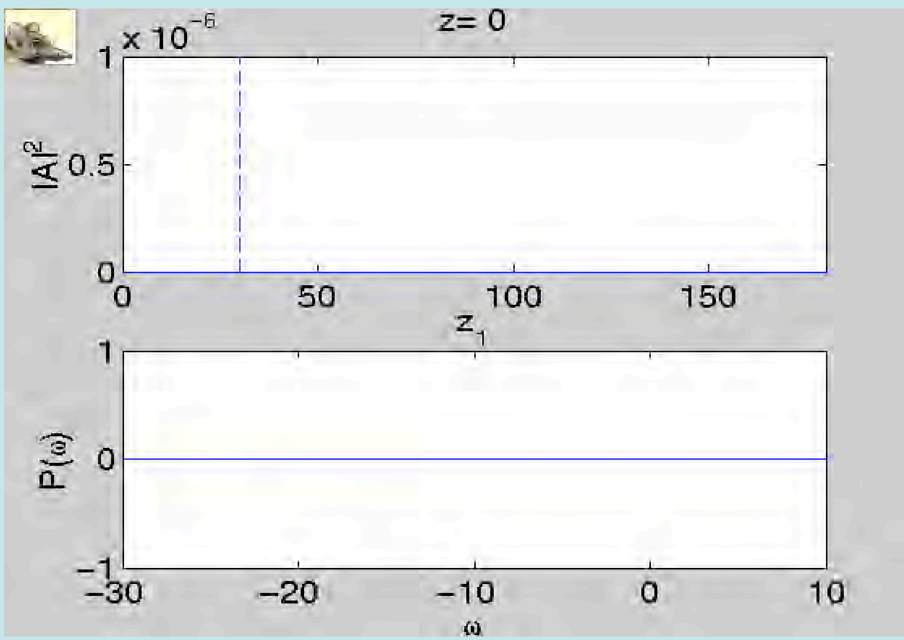
Full width

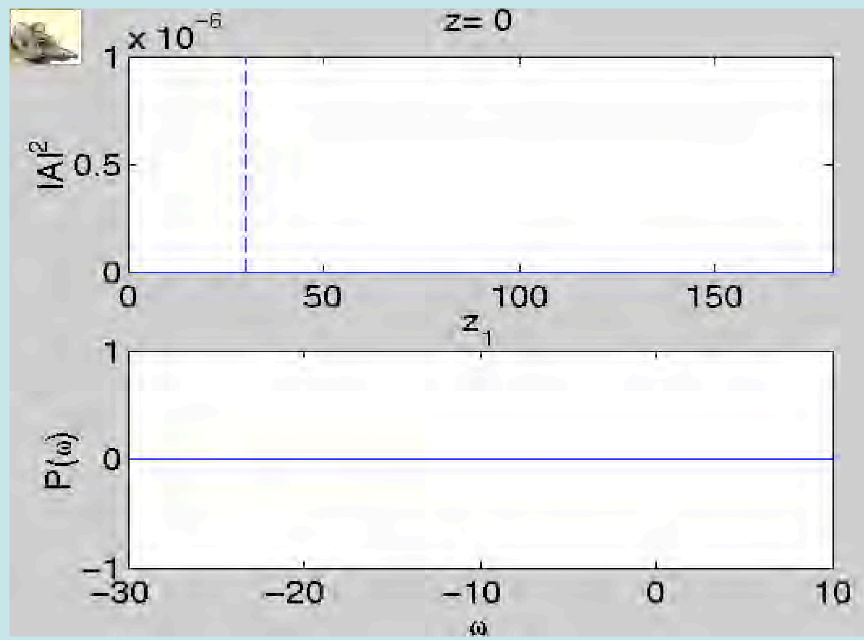
Continuous classical limit

(ref. 8)


z= 0
x 10^-6
|A|^2
0 20 40 60 80 100 120
z_1
P(ω)
−30 −20 −10 0 10
ω

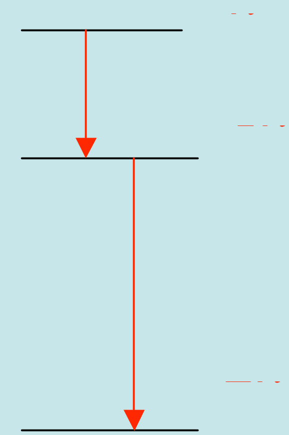

z= 0
x 10^-6
|A|^2
0 50 100 150
z_1
P(ω)
−30 −20 −10 0 10
ω


z= 0
x 10^-6
|A|^2
0 50 100 150
z_1
P(ω)
−30 −20 −10 0 10
ω


z= 0
x 10^-6
|A|^2
0 50 100 150
z_1
P(ω)
−30 −20 −10 0 10
ω

Quantum limit : discrete resonance as in a cavity

“Intuitive description”



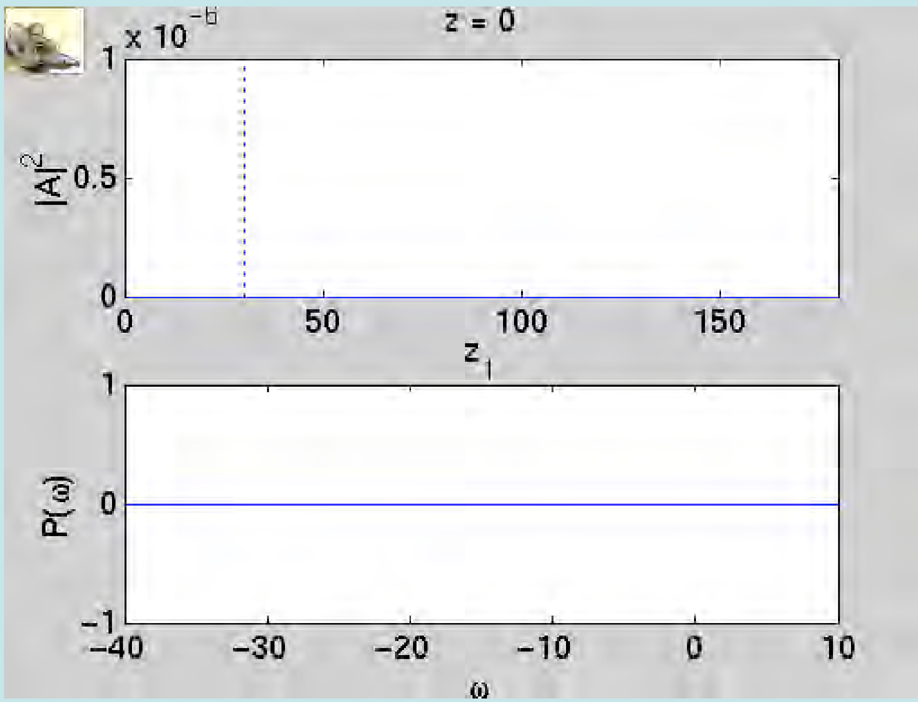
Only recoil : no absorption

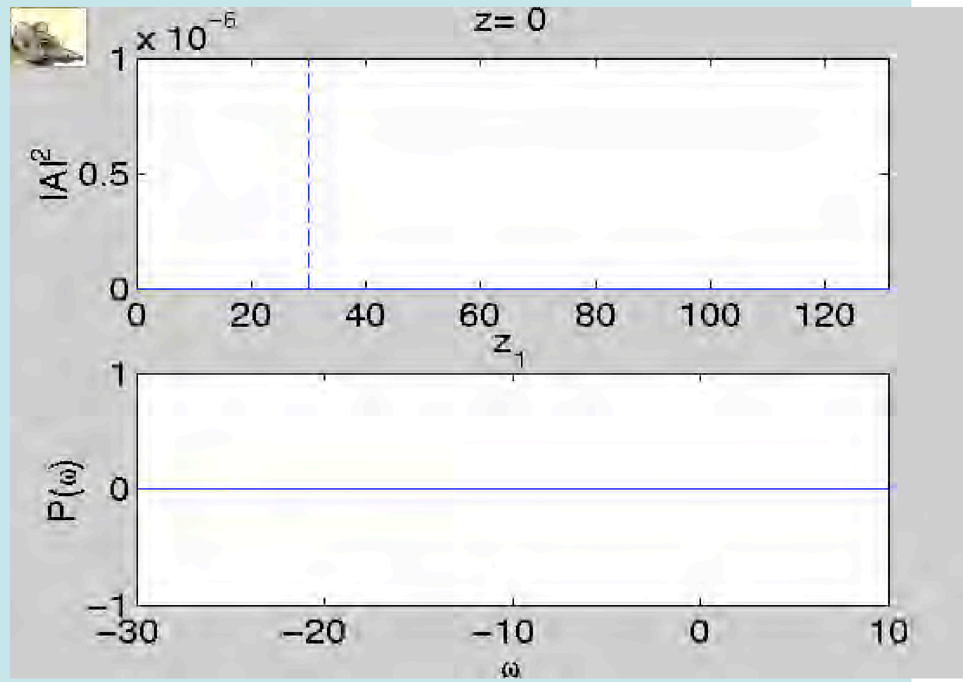
SASE

Quantum $\bar{\rho} = 0.05$

Classical $\bar{\rho} = 5$

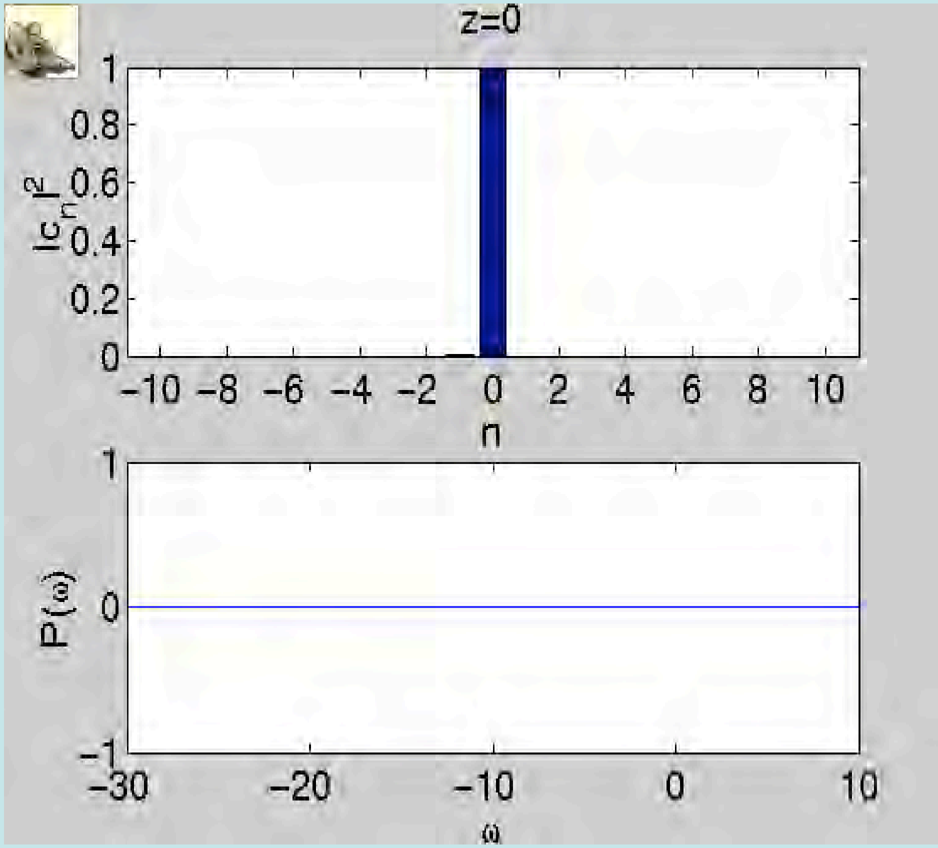
Evolution of radiation time structure in the electron rest frame



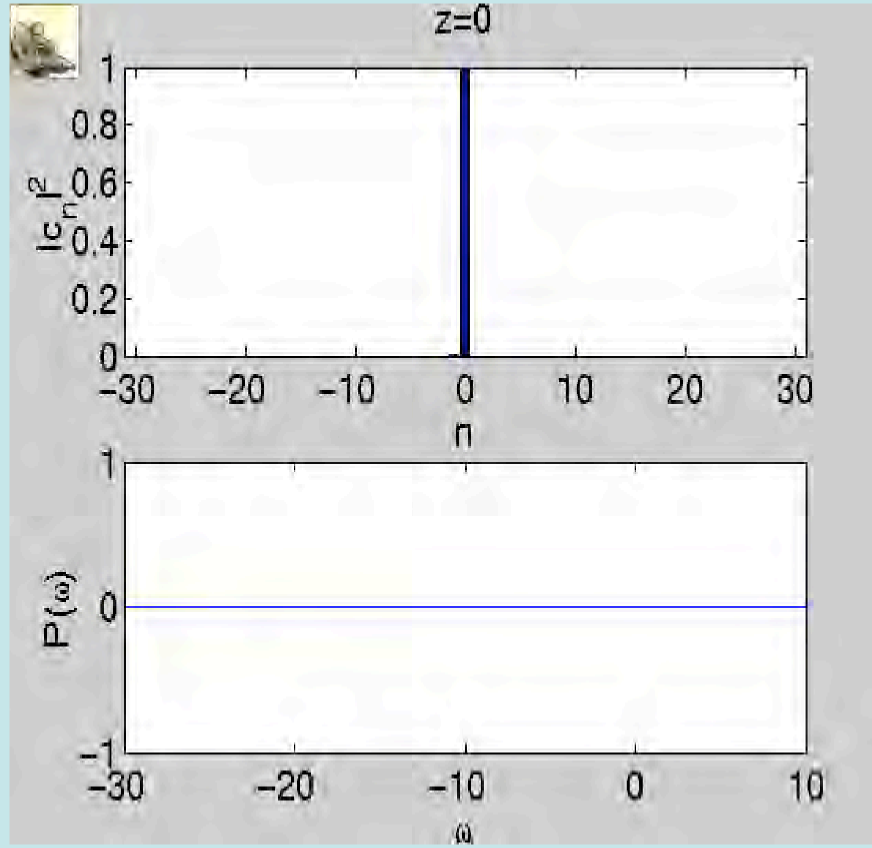


Simulation using QFEL model: Momentum distribution (average)

Quantum regime



Classical regime

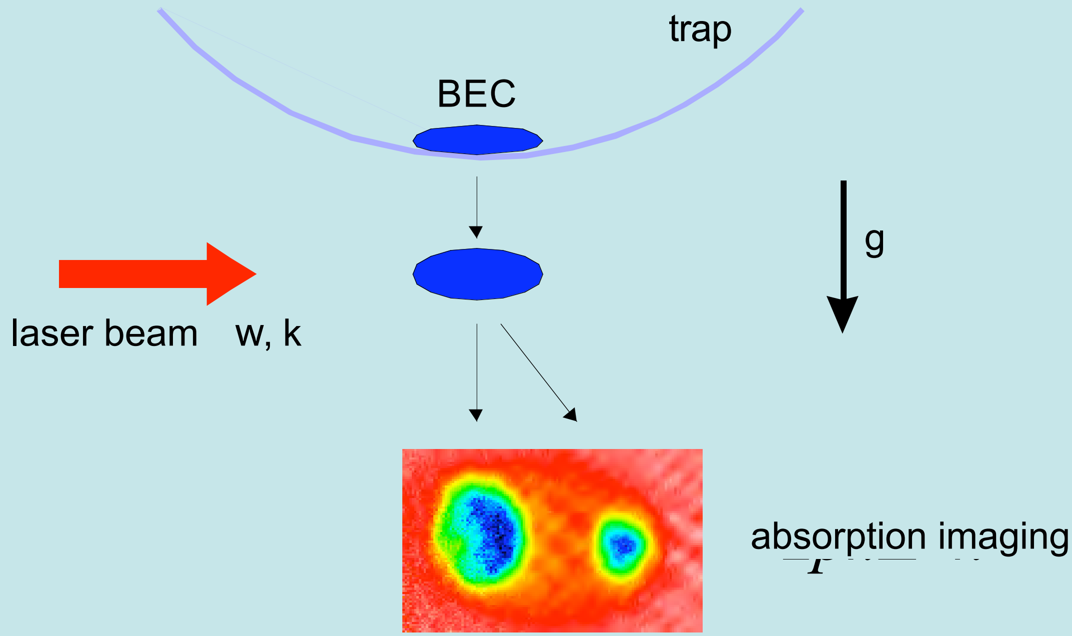


Classical behaviour : both n<0 and n>0 occupied

Quantum behaviour : sequential SR decay, only n<0

Experimental Evidence of Quantum Dynamics
The LENS (Firenze) Experiment

- **Production of an elongated ^{87}Rb BEC in a magnetic trap**
- **Laser pulse during first expansion of the condensate**
- **Absorption imaging of the momentum components of the cloud**



Experimental values:

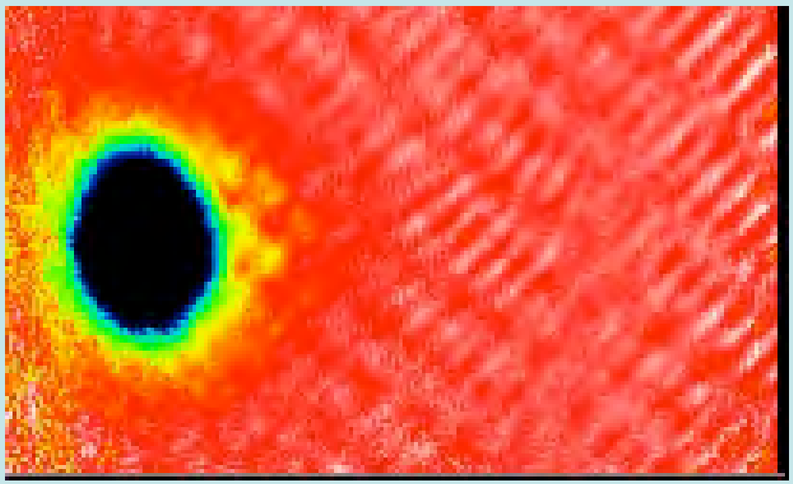
Δ = 13 GHz
w = 750 μm
P = 13 mW

R. B., F.S. Cataliotti, M.M. Cola, L. Fallani, C. Fort, N. Piovella, M. Inguscio

J. Mod. Opt. **51**, 785 (2004), Optics Comm. **233**, 155(2004) and Phys. Rev. A 71, 033612 (2005)

The Experiment

Temporal evolution of the population in the first three atomic momentum states during the application of the light pulse.

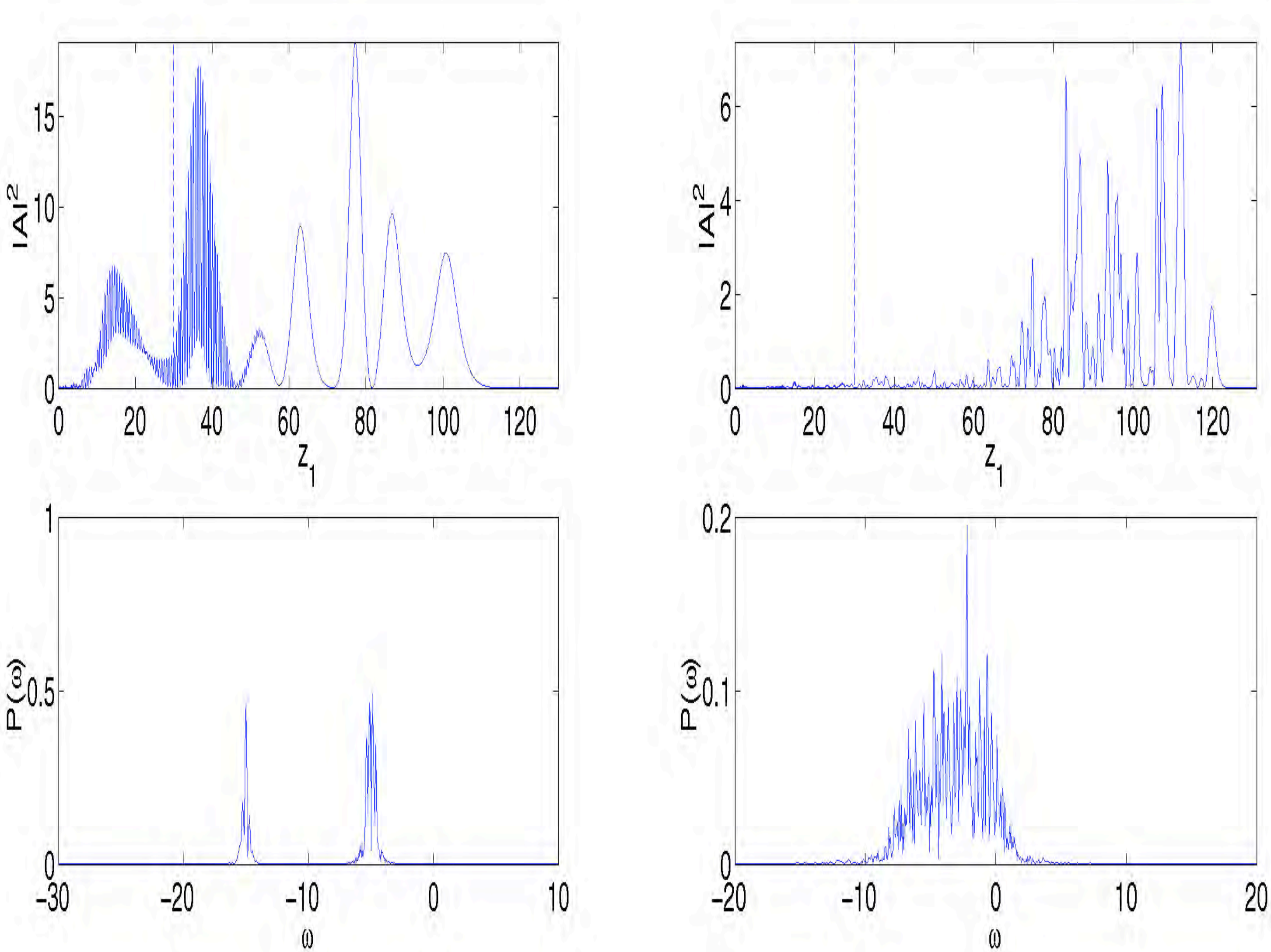


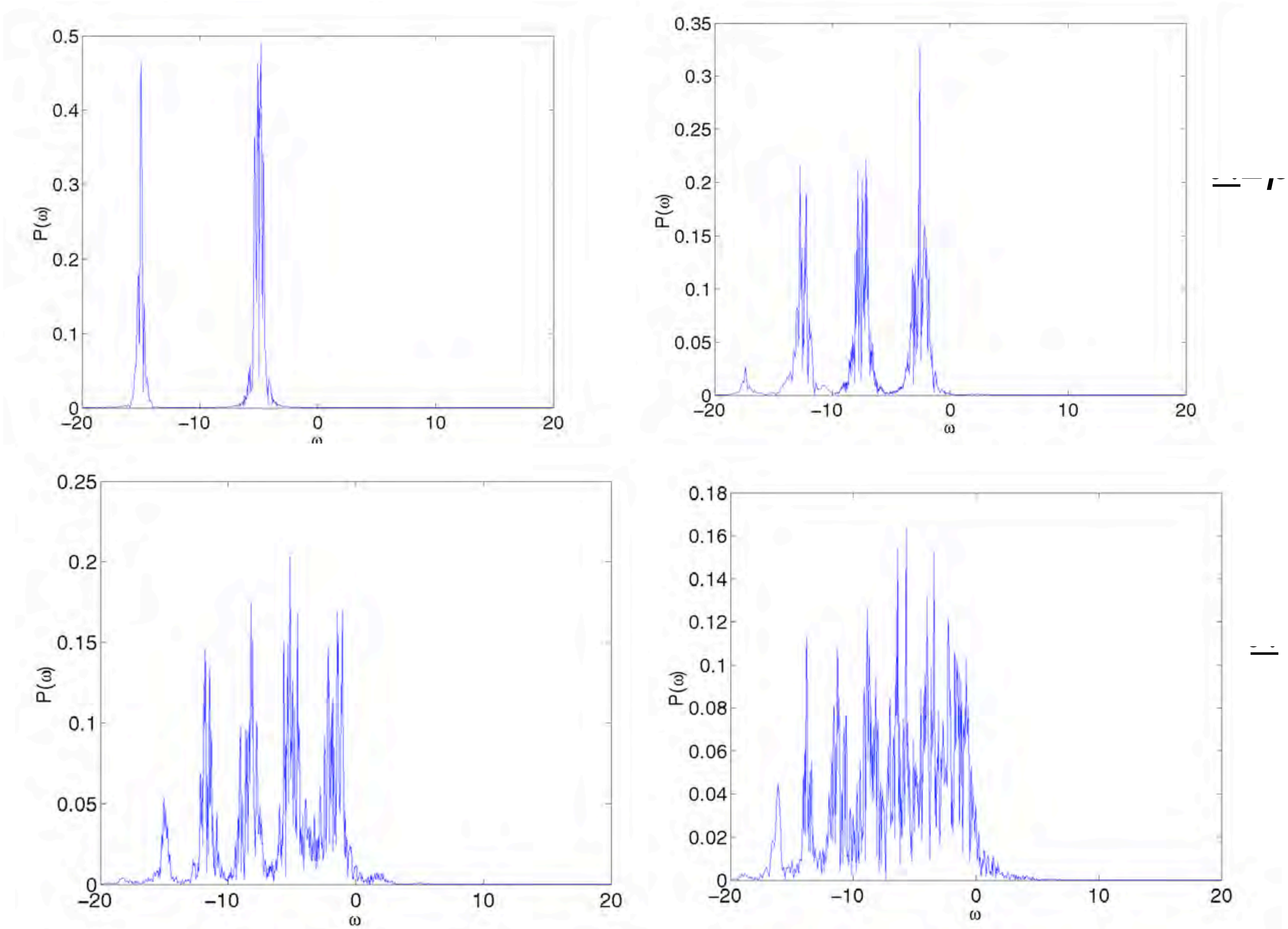
pump light

n=0 n=1 n=2

p=0

Quantum Classical





P(ω)
ω
P(ω)
ω
P(ω)
ω
P(ω)
ω

Conclusions

- Classical description of SASE valid IF
- IF one has quantum SASE: the gain bandwidth decreases as $\sqrt{}$ and $\sqrt{}$ ⇨ line narrowing, temporal coherence.
- Multiple lines Spectrum:
  - separation , linewidth $\sqrt{}$
- Classical limit: increasing separation linewidth → continuous spiky classical spectrum.
- Experimental evidence of Quantum FEL in a BEC
- QFEL Project

For experimental setup see R.B., NIM A 546 (2005) 634, proc. FEL conf. 2005

Quantum Free Electron Laser

QFEL

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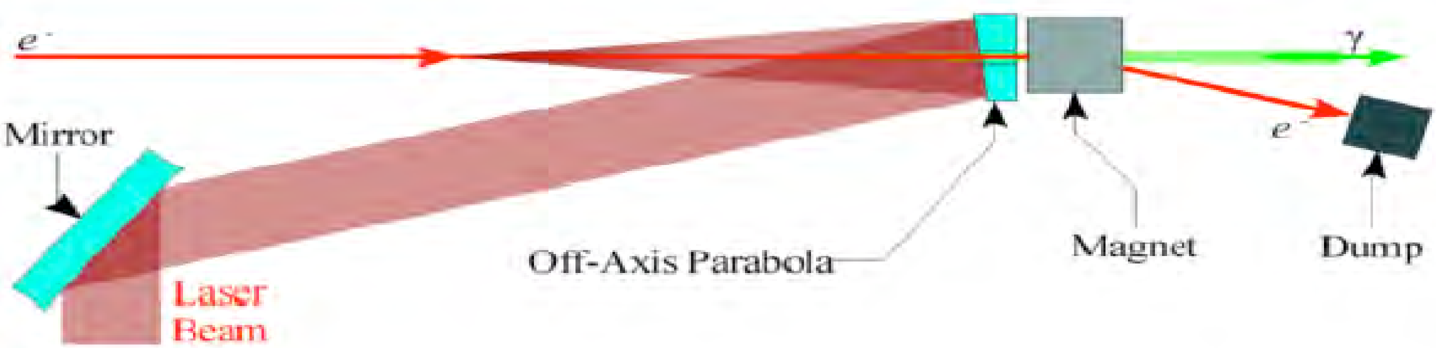
SPARC + FLAME ==> PLASMON X + QFEL

Ingredients of Quantum FEL SASE:

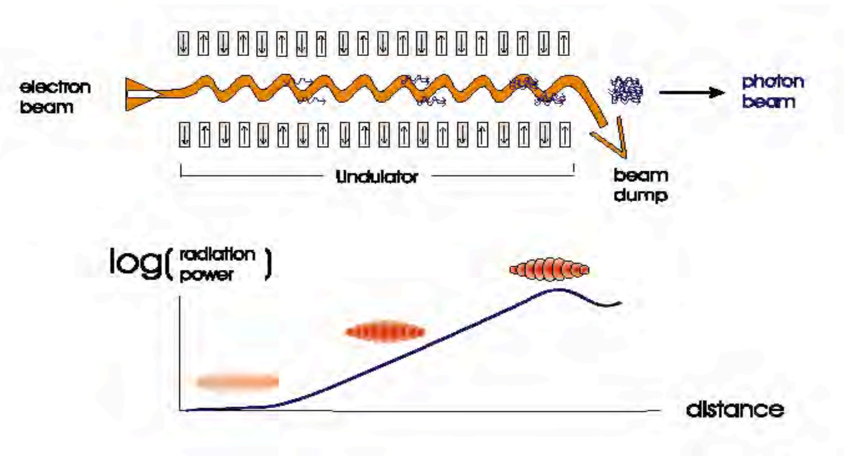
- electron beam 15-100 MeV, 100 A , $\varepsilon_n < 2$ mm mrad
- Laser wiggler at 0.8 micron , 10-100 TW (Ti:Sa)

Both under development for SPARC/PLASMON_X



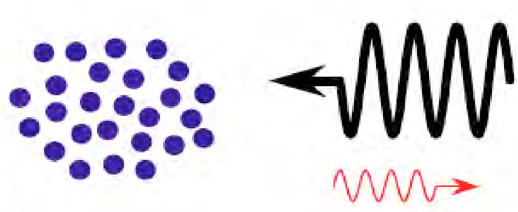
Radiation in QFEL:

- ~10^{10} photons at λ ~1 Å for some ps
- monocromaticity ($\Delta\lambda/\lambda<10^{-4}$)



Classical FEL SASE experiments (DESY, SLAC):
- GeV linac (Km) and long undulators (100 m)
- Radiation spectrum broad and chaotic (spikes)
- High cost (10^9 U$) and large dimensions

Quantum FEL SASE:
- quantum purification (monocromatic spectrum)
- must use a laser undulator
- reduced cost (10^6 U$) and compact devise (m)

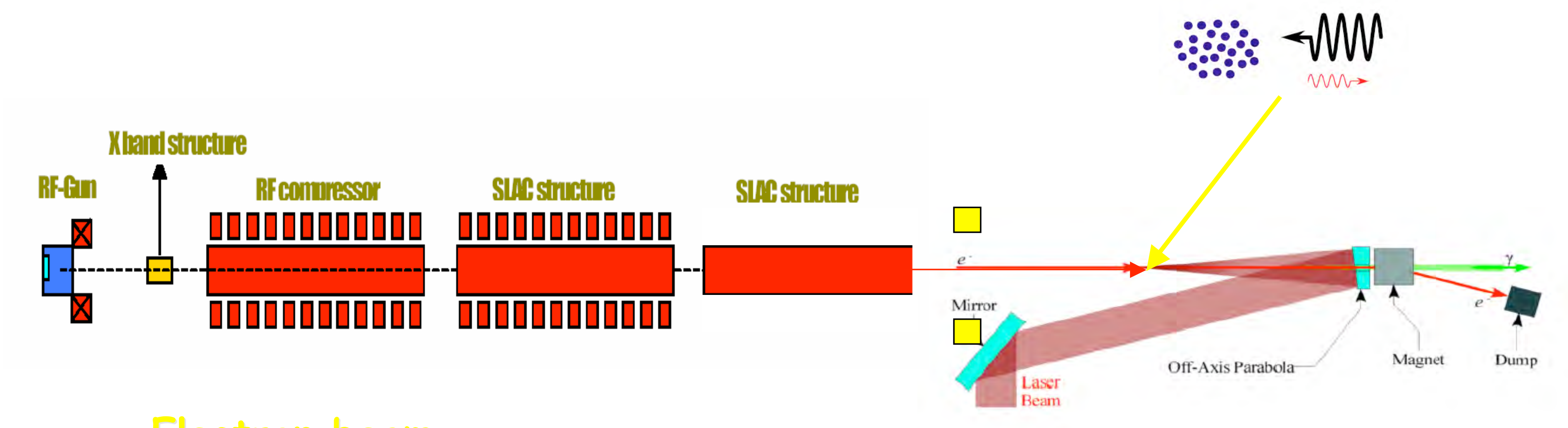


QFEL

Previous studies are based on a 1D quantum model.

Future work: analytical/numerical study of a 3D Quantum model in order to demonstrate the feasibility of a Quantum SASE experiment at INFN-LNF

Preliminary parameters list for QFEL



Electron beam

E [MeV]	20
I [A]	40
ε_n [μm]	1
$\delta\gamma/\gamma$ [%]	0.03
β^* [mm]	0.5-1

Laser beam

λ [μm]	0.8
P [TW]	1
E [J]	4
w_o [μm]	5-10
Z_r [μm]	80-300

QFEL beam

λ_r [A]	1.7
P_r [MW]	0.3


Thank you and see you in my office in Brazil