Influence of optical feedback on the coherence properties of FELs

S. Bielawski, C. Evain, C. Szwaj

Lab. PhLAM/CERLA, université de Lille 1 (France)

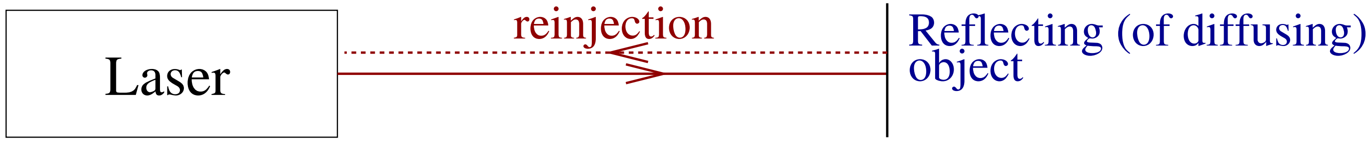
M. Hosaka, A. Mochihashi, M Katoh

UVSOR, Institute for Molecular Science, Okazaki (Japan)

M.E. Couprie

CEA/Synchrotron SOLEIL, Gif−sur−Yvette (France)

Starting point: Optical feedback in classical lasers

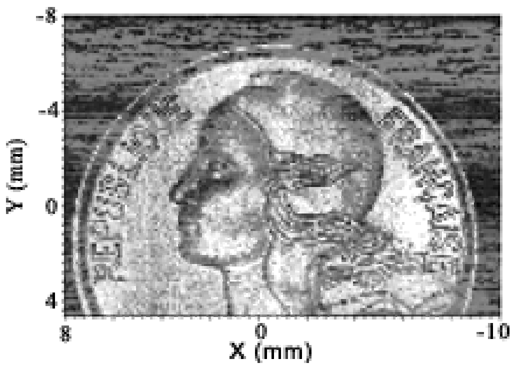


Effects of small feedback:

CW laser destabilization

Ex.: Diode lasers Lang & Kobayashi [IEEE JQE 16, 357 (1980)]

Ex. 2: Use in sensors:



coin detected under 1 cm of milk

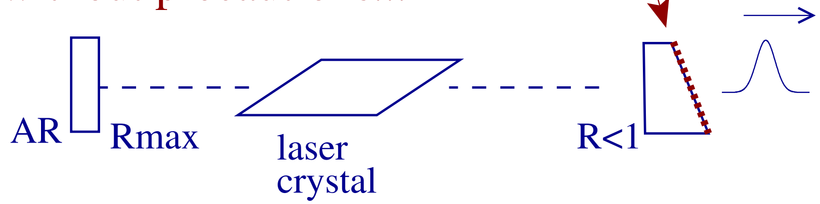
See Lacot et al. PRA 64, 043815 (2001)

1e−7 – 1e−13 of reinjection...

Pulsed lasers (mode−locked)

– No pulses without precautions...

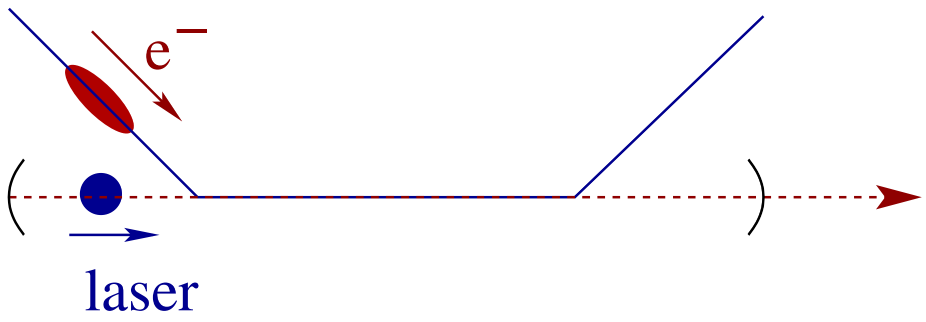
AR+ angle!

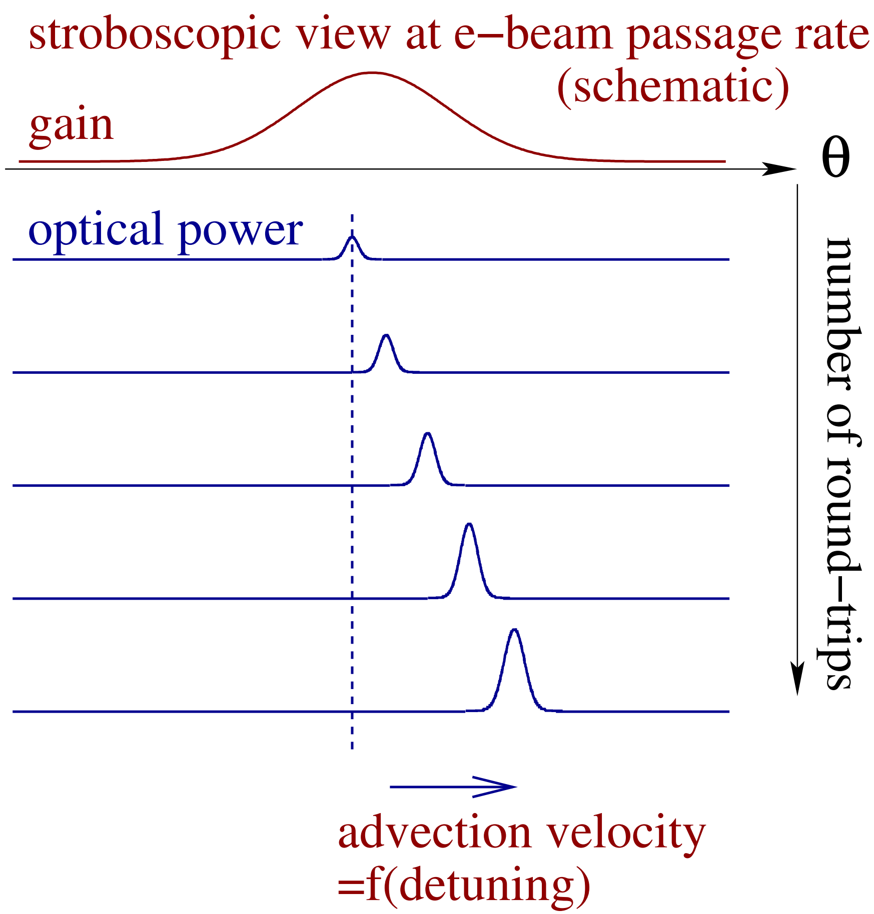


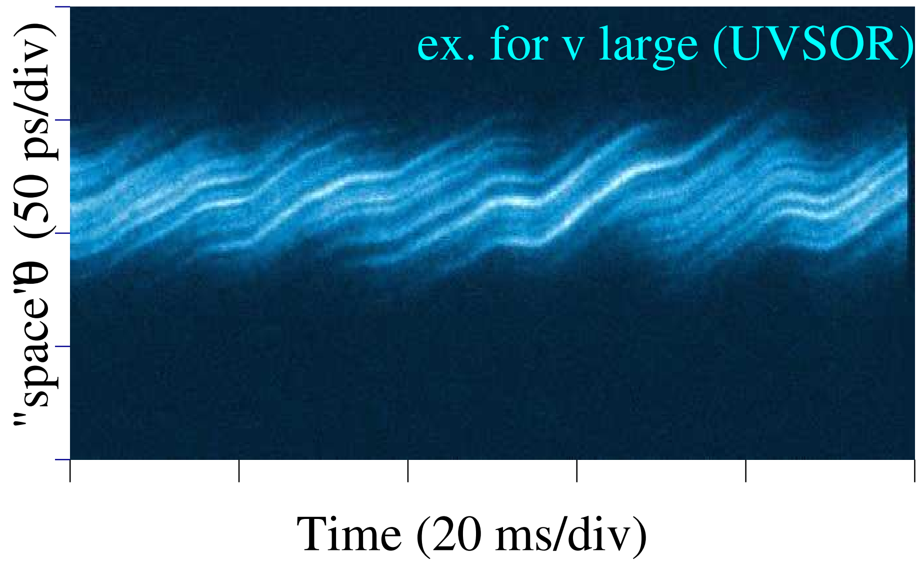
– Stabilization of operation:
Coherent Photon Seeding (CPS)
[Beaud et al. Opt. Commun. 80, 31 (1990)]

– *Pulse shortening (Additive Pulse Mode−Locking)*

FEL Oscillator = mode−locked laser with synchronous pump





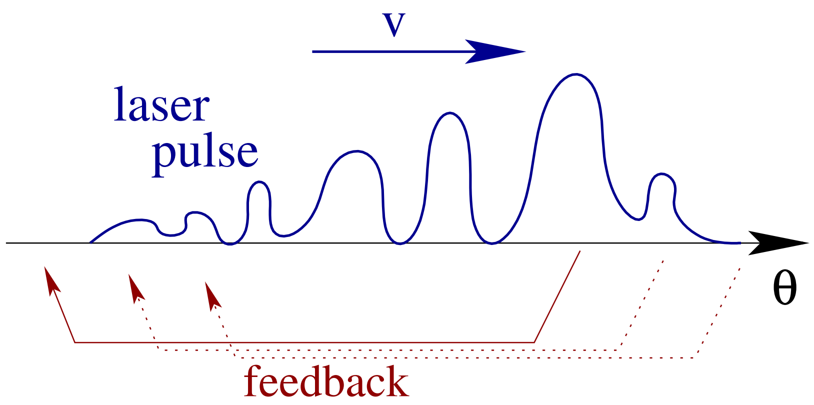


Question:

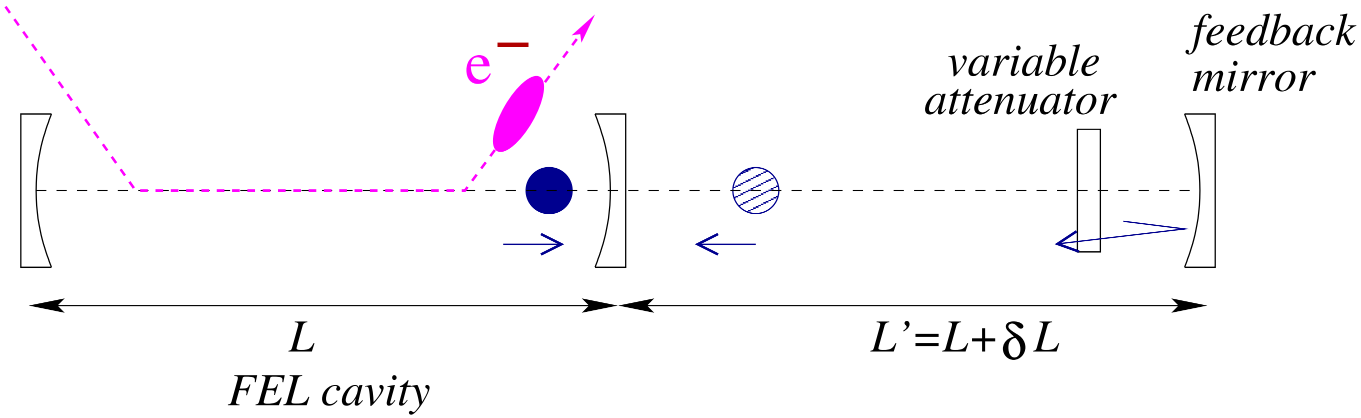
In classical mode−locked lasers,
Coherent Photon Seeding (CPS)
is able to stabilize this type of turbulence
using very small feedback

What about FEL oscillators?

Feedback Principle:



1) Take a copy of the field pattern
2) Seed the laser with the shifted copy
(shift left if the advection goes to the right)



Technique known in synchronously pumped lasers:

- theory.: [New, Opt. Lett. 15, 1306 (1990)]
- Experiment. [Beaud et al. Opt. Commun 80, 31 (1990)],

and in Optical Parametric Oscillators:

(theory only) Scroggie et al. JOSA B17, 84 (2000)

Note: not a lot of direct experimental studies...

e: complex envelope of the laser pulse

$$e_T + v e_\theta = -e + G f(\theta)(e + e_{\theta\theta}) + \sqrt{\eta}\xi + \alpha e(\theta + \tau)$$

α^2 : fraction of reinjected power

τ : feedback delay

$G =$ decreasing function of energy spread σ^2

$$\frac{d\sigma^2(T)}{dT} = -\frac{1}{T_s}\left(1 - \sigma^2 + \int_0^L |e(\theta, T|^2 d\theta\right)$$

SB et al. PRL 85, 034801 (2005)

T: (continuous) time associated with the number of round−trips

θ : time resolving the pulse shape (relevant as a "space")

v : proportional to the freq. mismatch between e−beam and cavity

Ts : synchrotron damping time

Ts : synchrotron damping time

Laser "field master equation":

H. Haus IEEE J.QE 11, 323, 1975

Dattoli et al. PRA37, 4376 (1987)

P. Elleaume IEEE JQE21, 1012 (1985)

+ FEL gain saturation

see: G. De Ninno, Eur. Phys. J D. 22, 269 (2003)

Feedback modeling:

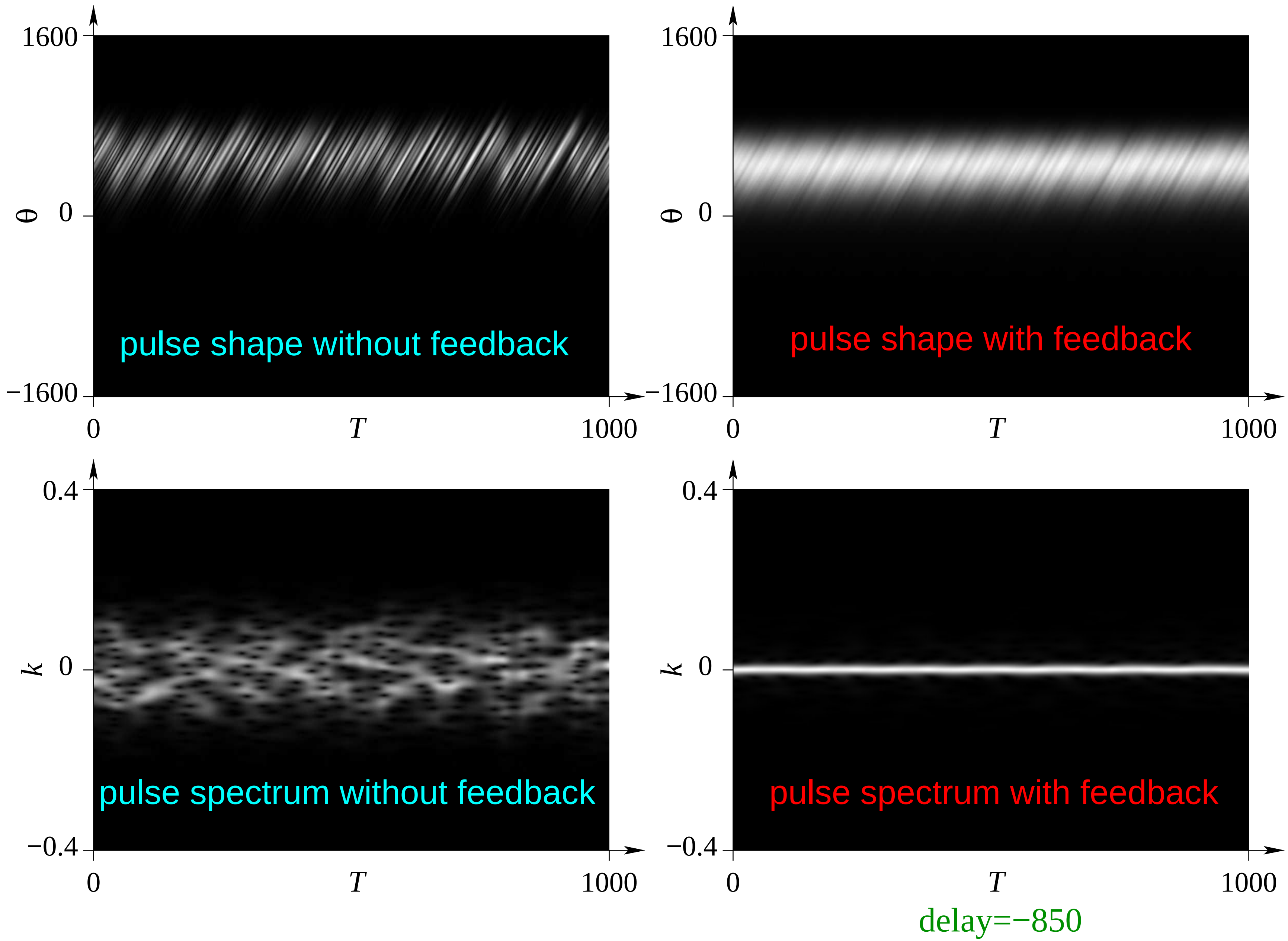
New, Opt. Lett. 15, 1306 (1990)

Scroggie et al. JOSA B17, 84 (2000)

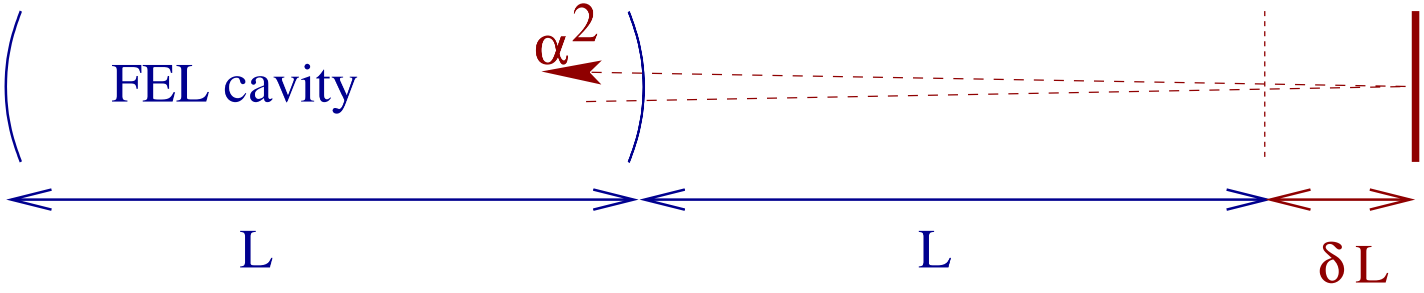
Note: very different from opto−electronic feedback: SB et al. PRE69, 045502 (2004)

DeNinno & Fannelli PRL 92, 094801 (2004)

Numerical results for the FEL

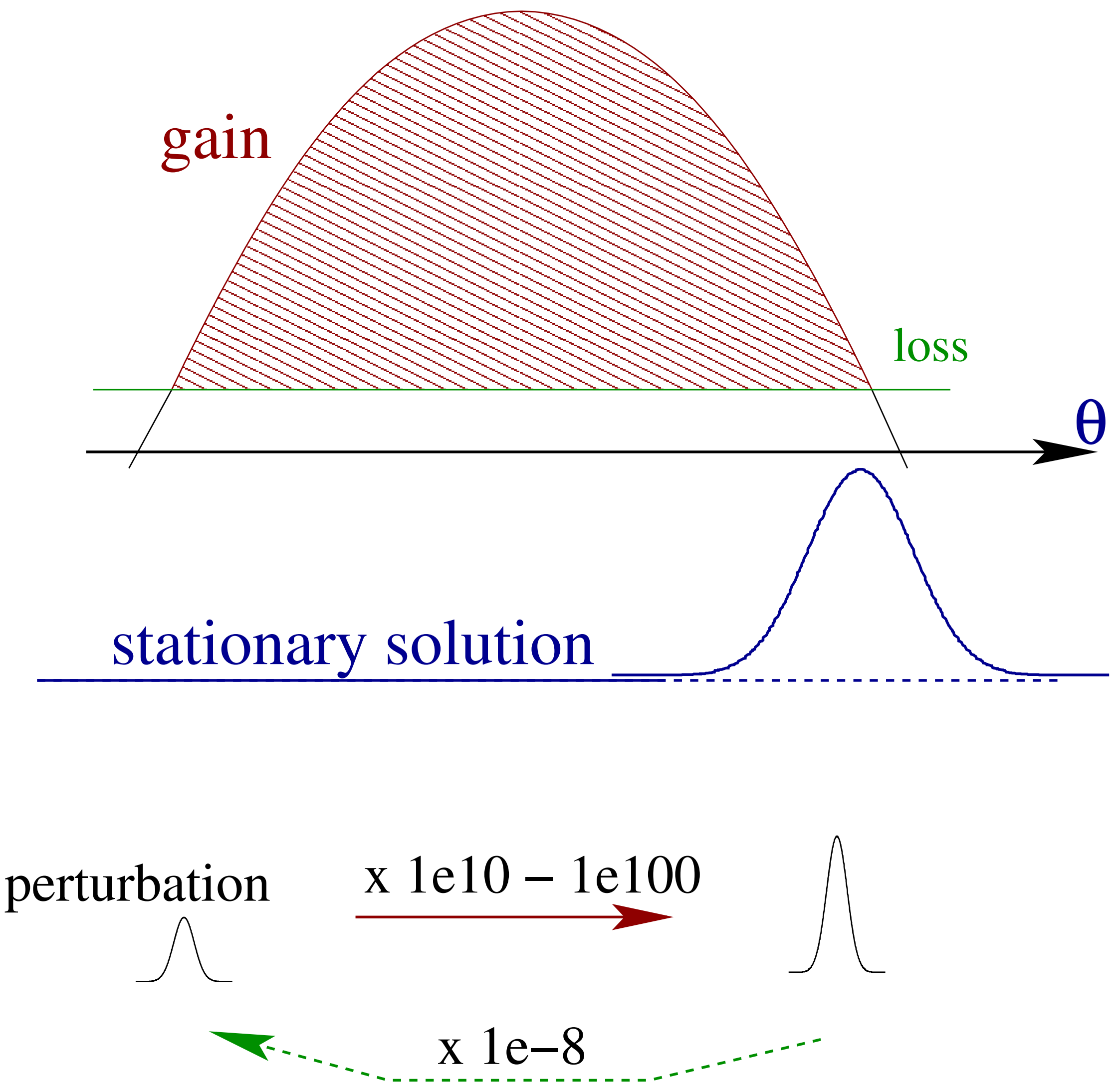


Typical feedback parameters:



	Model parameters (adimensional)	Associated experimental control parameters
delay	τ =O(bunch length)	δL =O(cm) for UVSOR
fraction reinjected (min)	α^2 =O(η)	power reinjected = O(spont. em. noise)

Towards interpretations of the underlying mechanism

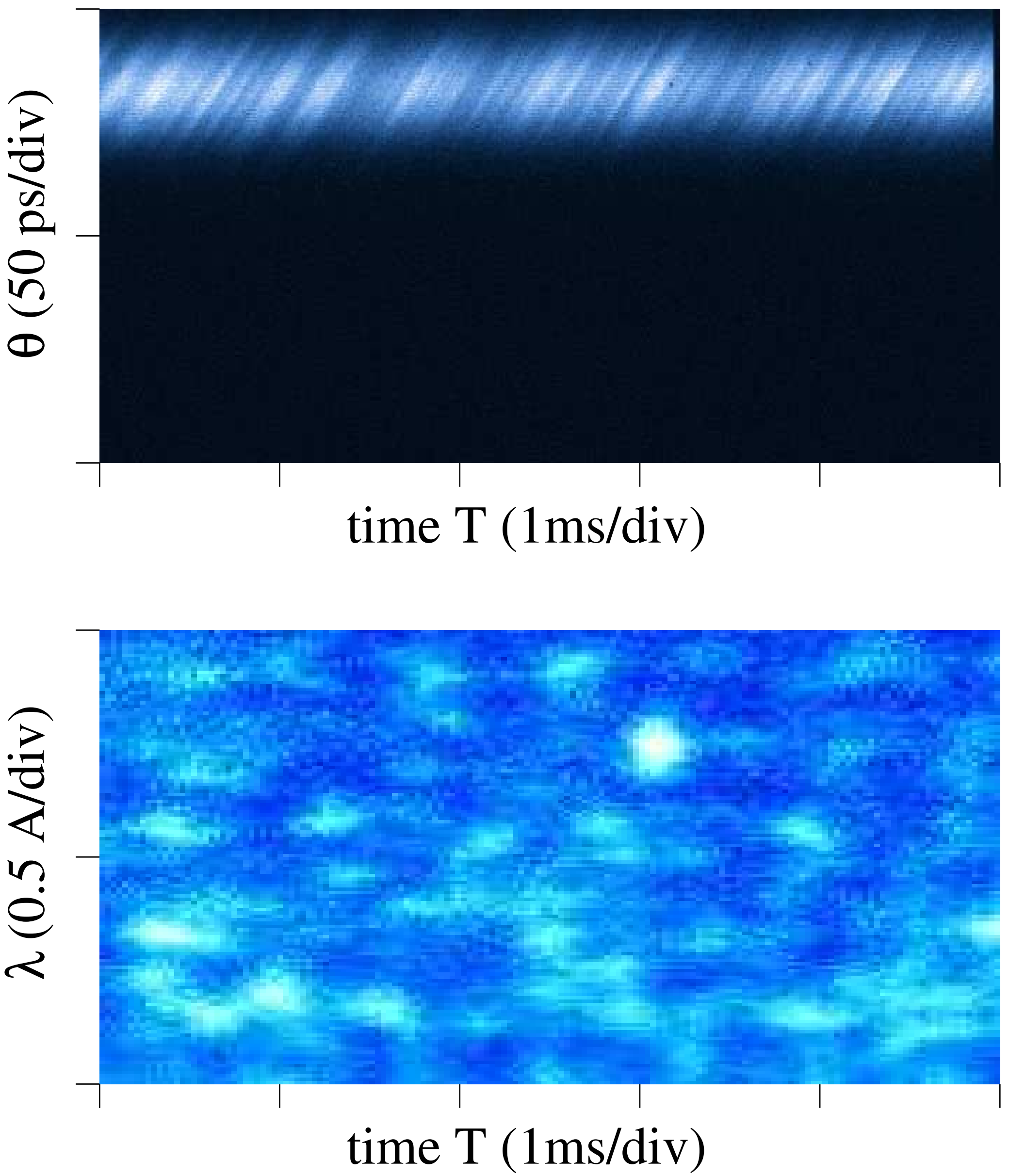


1) Create a deterministic stationary solution

2) Saturate the gain to prevent "transient growth"

Experimental results: UVSOR FEL, 420 nm

without feedback



Experimental results: UVSOR FEL, 420 nm

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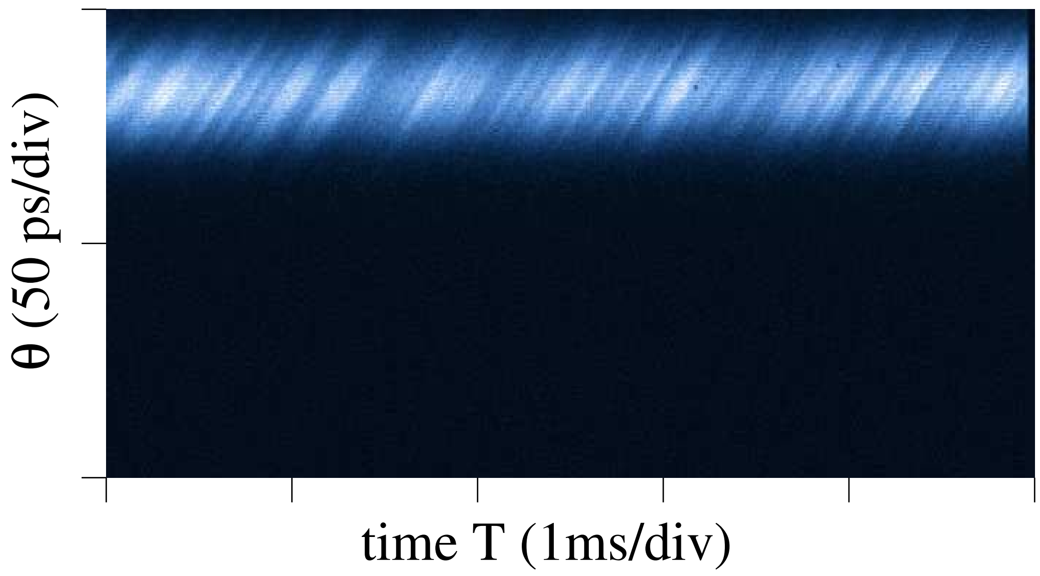
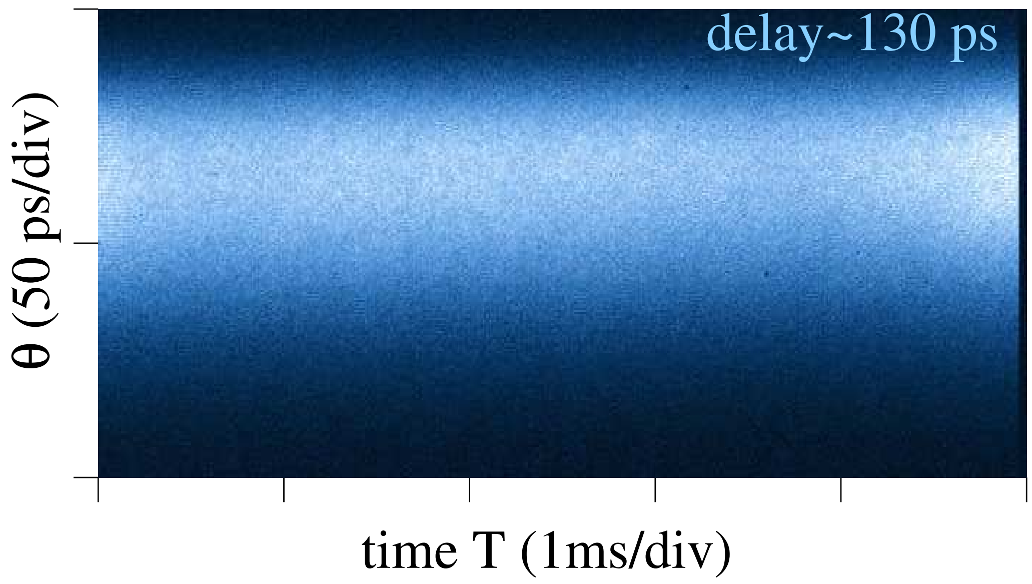
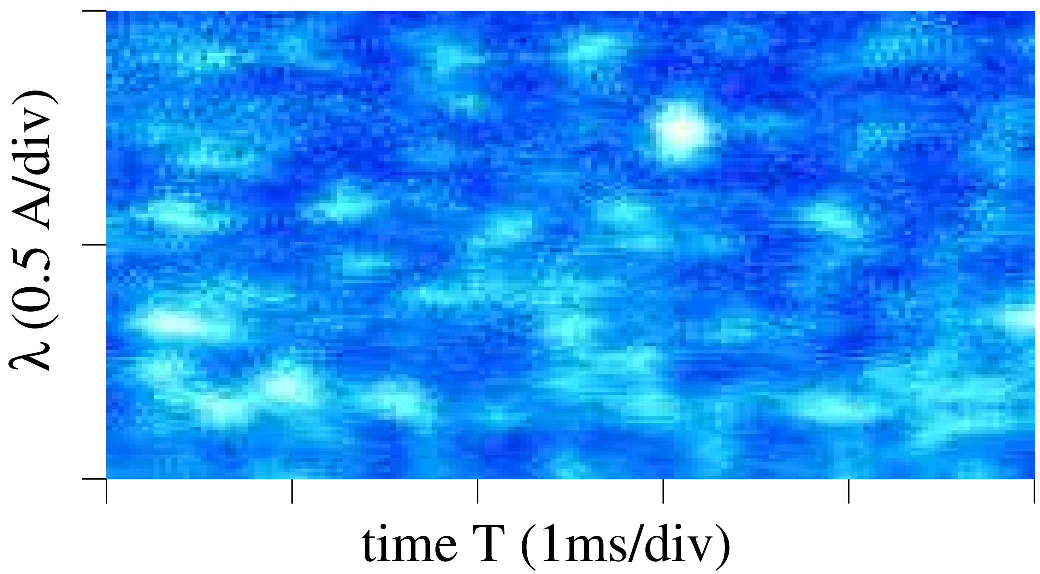
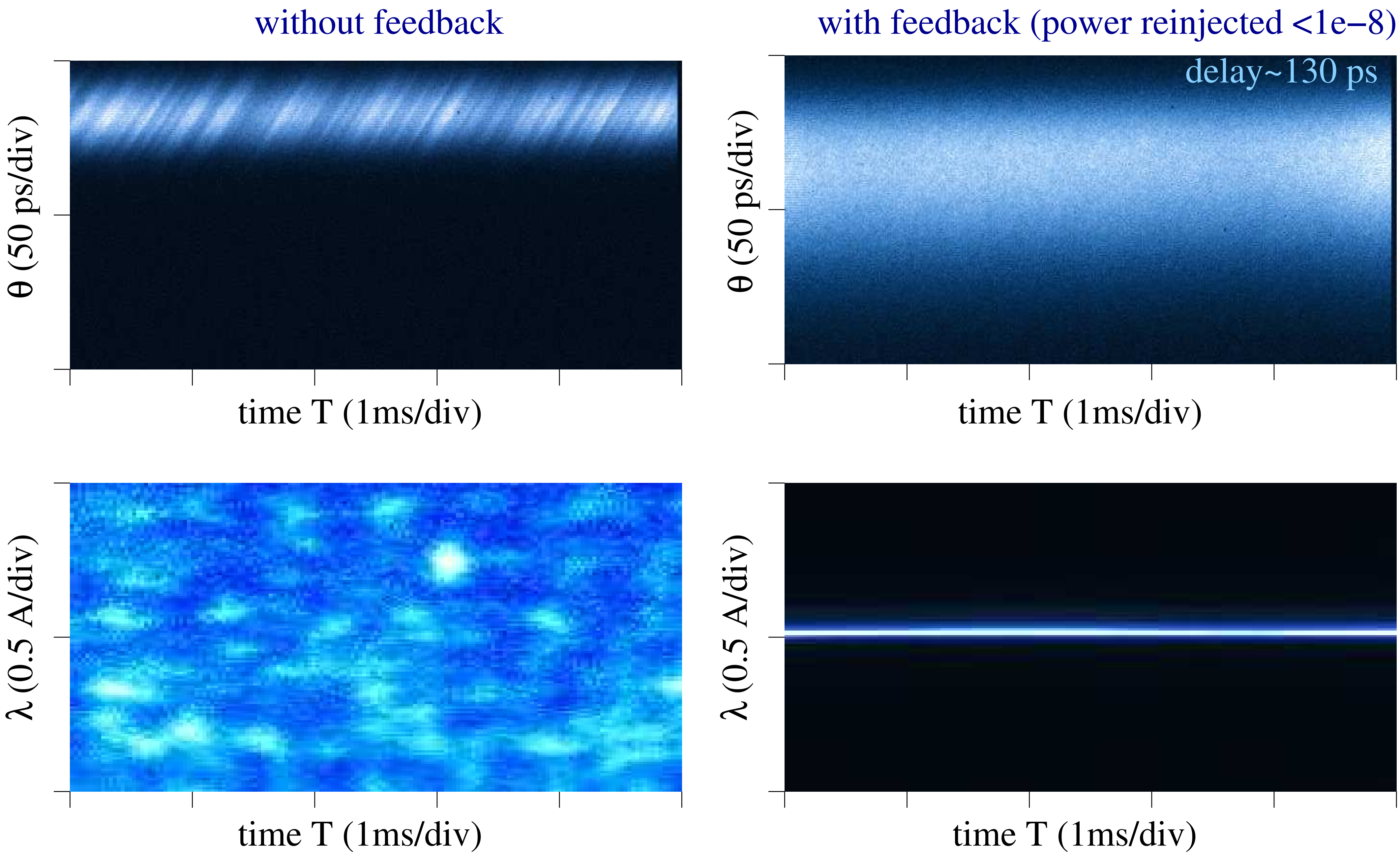


with feedback (power reinjected <1e−8)

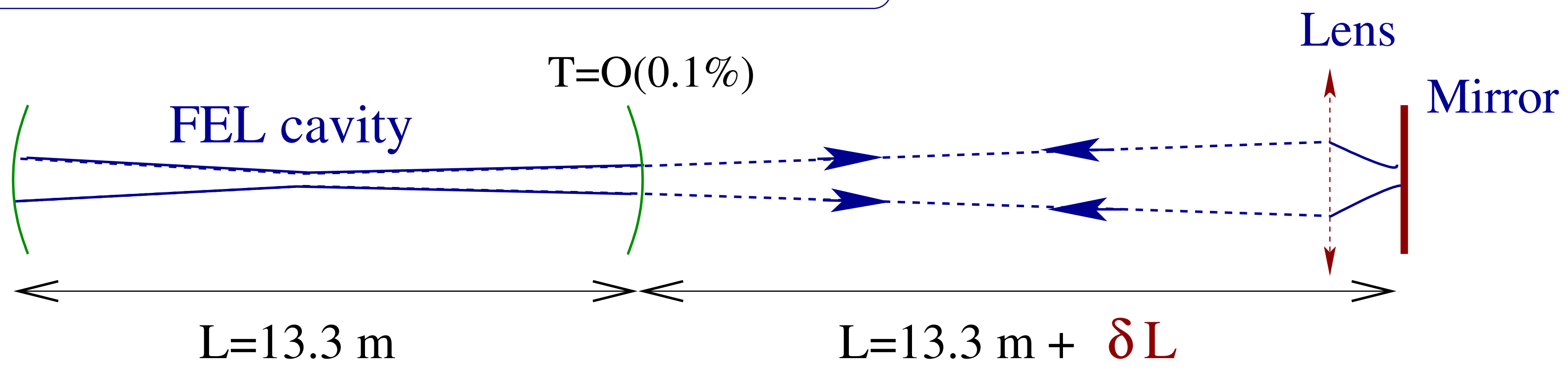


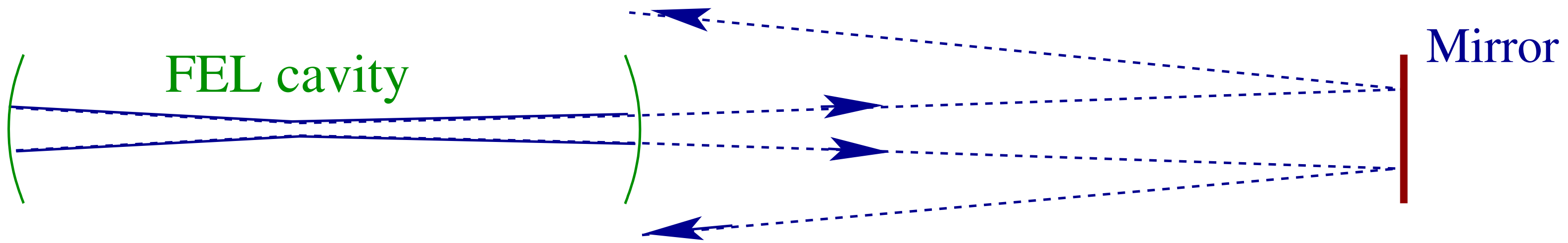


Experimental results: UVSOR FEL, 420 nm



More details on the experimental setup

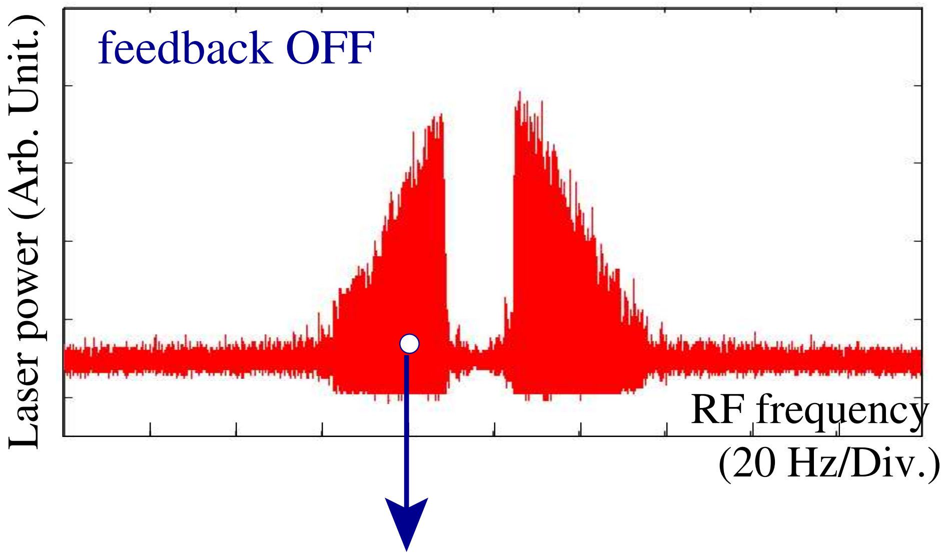




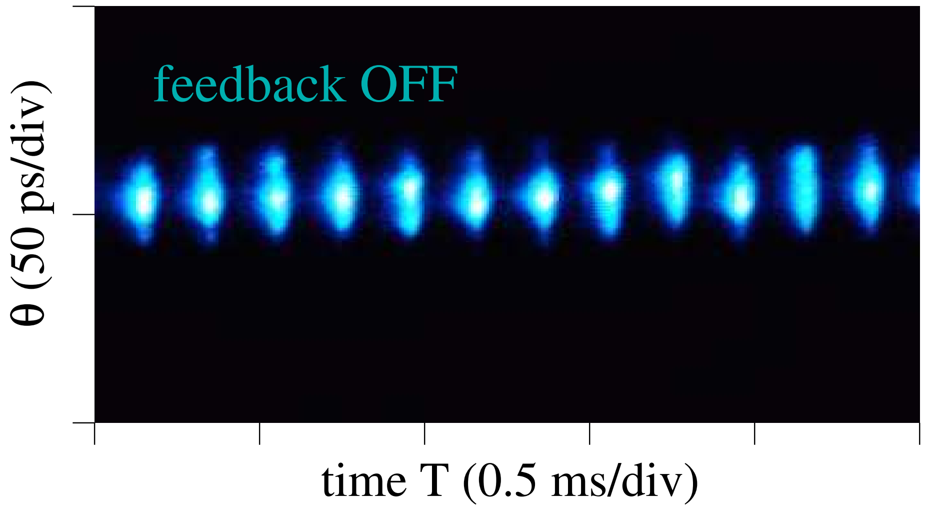
at the output coupler: factor 10 between the laser waist and the feedback waist...

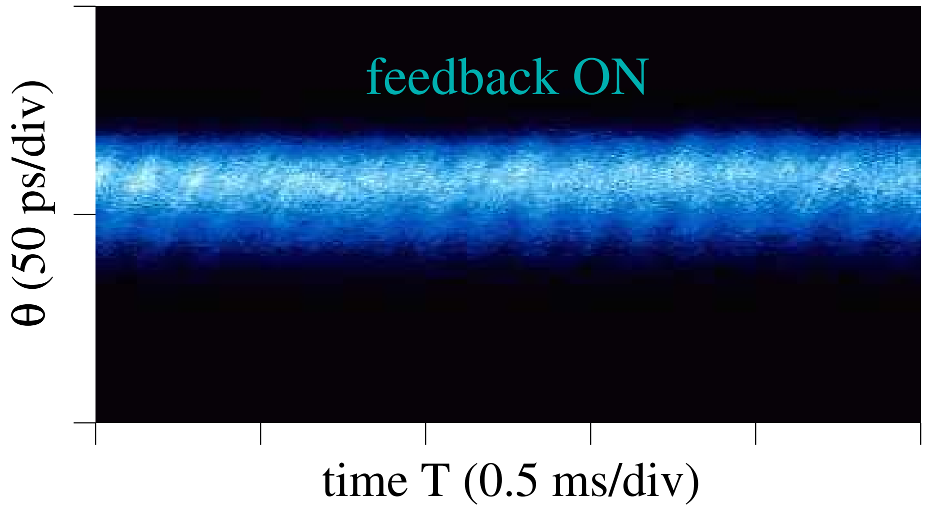
- Very low sensitivity to tranverse misalignments
- lower bound to the fraction of intracavity power that is reinjected : 10^{-8}

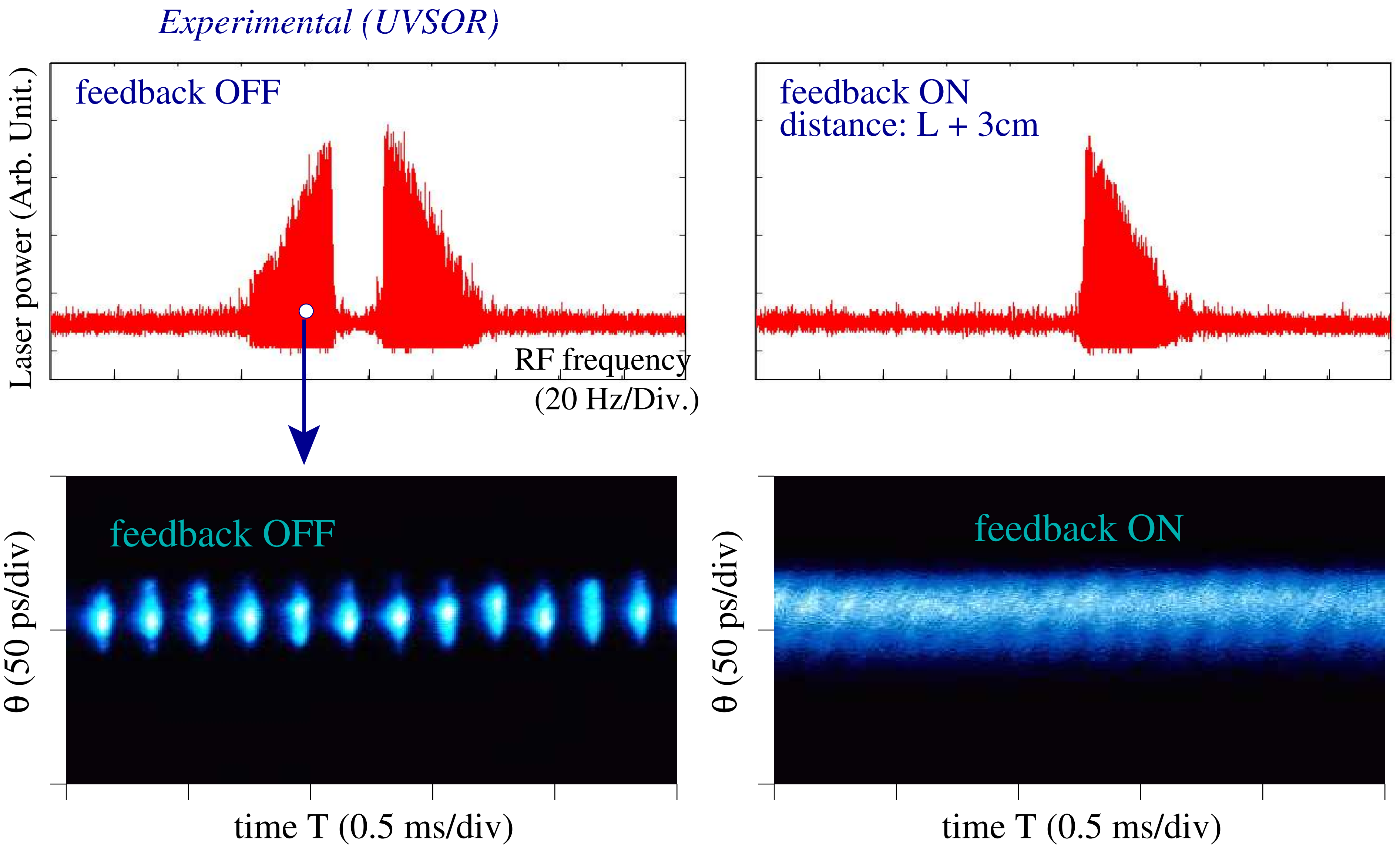
Experimental (UVSOR)



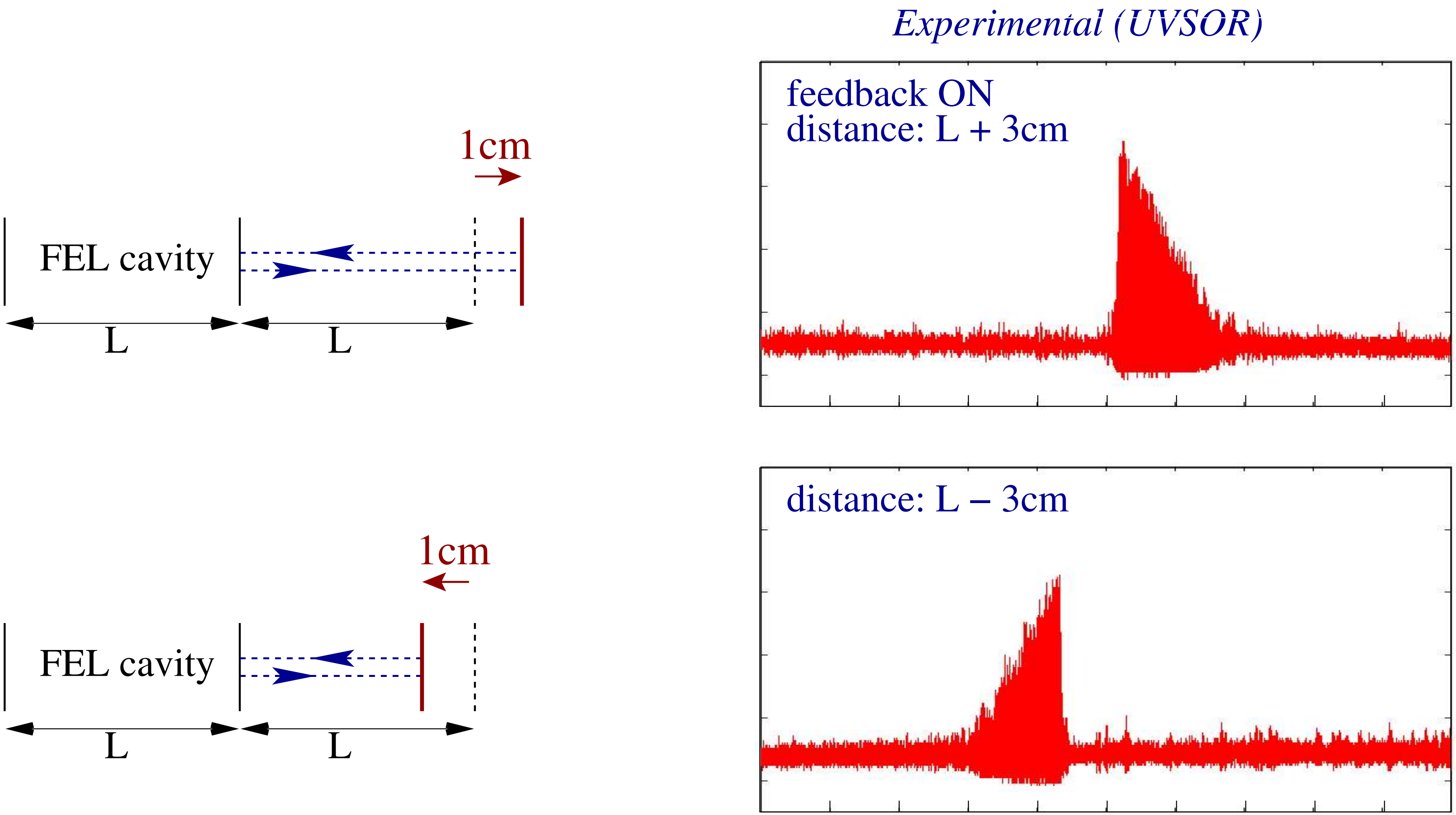
FEL in a pulsed regime ?







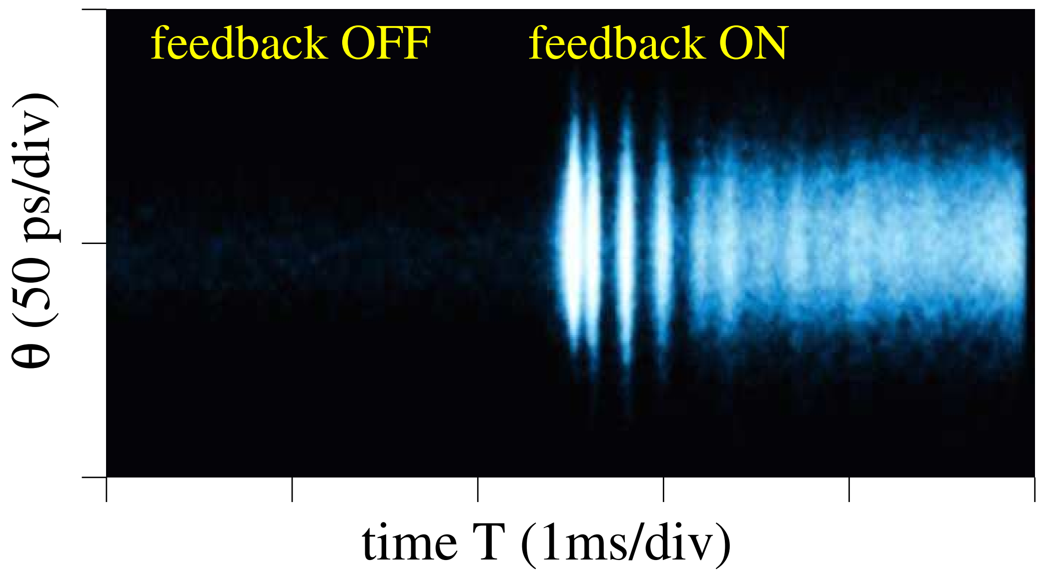
Experimental (UVSOR)
feedback OFF
Laser power (Arb. Unit.)
RF frequency
(20 Hz/Div.)
feedback ON
distance: L + 3cm
feedback OFF
θ (50 ps/div)
time T (0.5 ms/div)
feedback ON
θ (50 ps/div)
time T (0.5 ms/div)

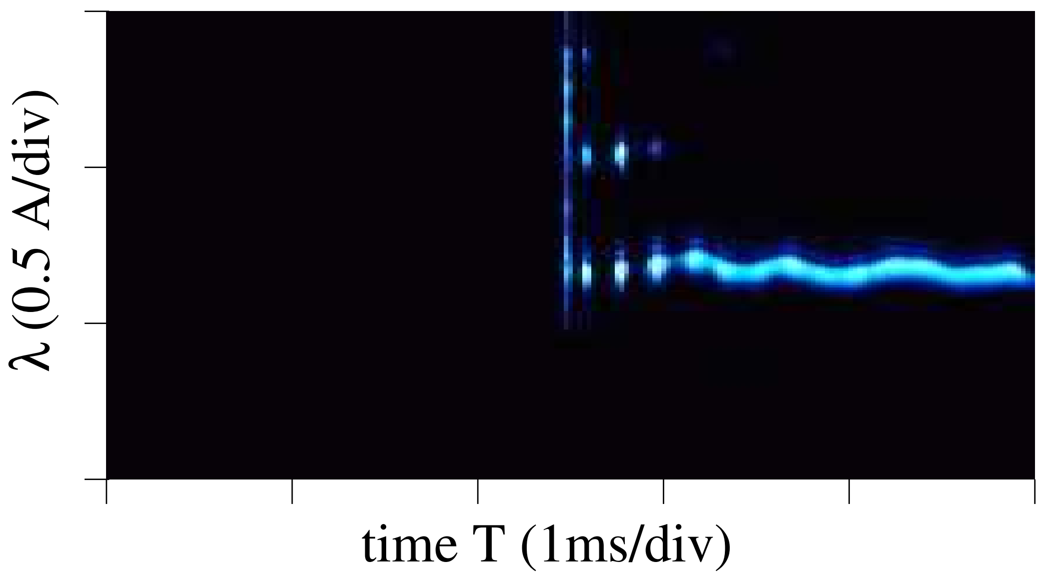


Experimental (UVSOR)
1cm
FEL cavity
L
L
feedback ON
distance: L + 3cm
1cm
FEL cavity
L
L
distance: L – 3cm

FEL strongly detuned (practically "OFF")

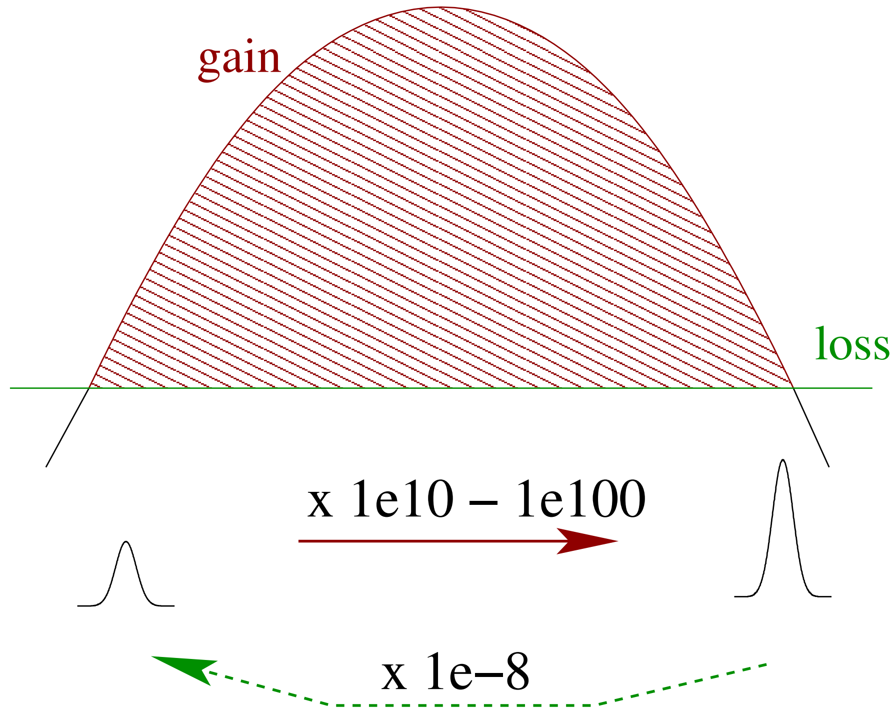
Chopper on the feedback path





Note:
gain=O(1e−2)
cavity loss=O(1e−3)
reinjection=O(1e−8)

! Adequate picture: "Transient growth"



Conclusion

– FEL oscillators are very sensitive to optical feedback
if the feedback is at a distance: n x cavity_length + O(bunch length)

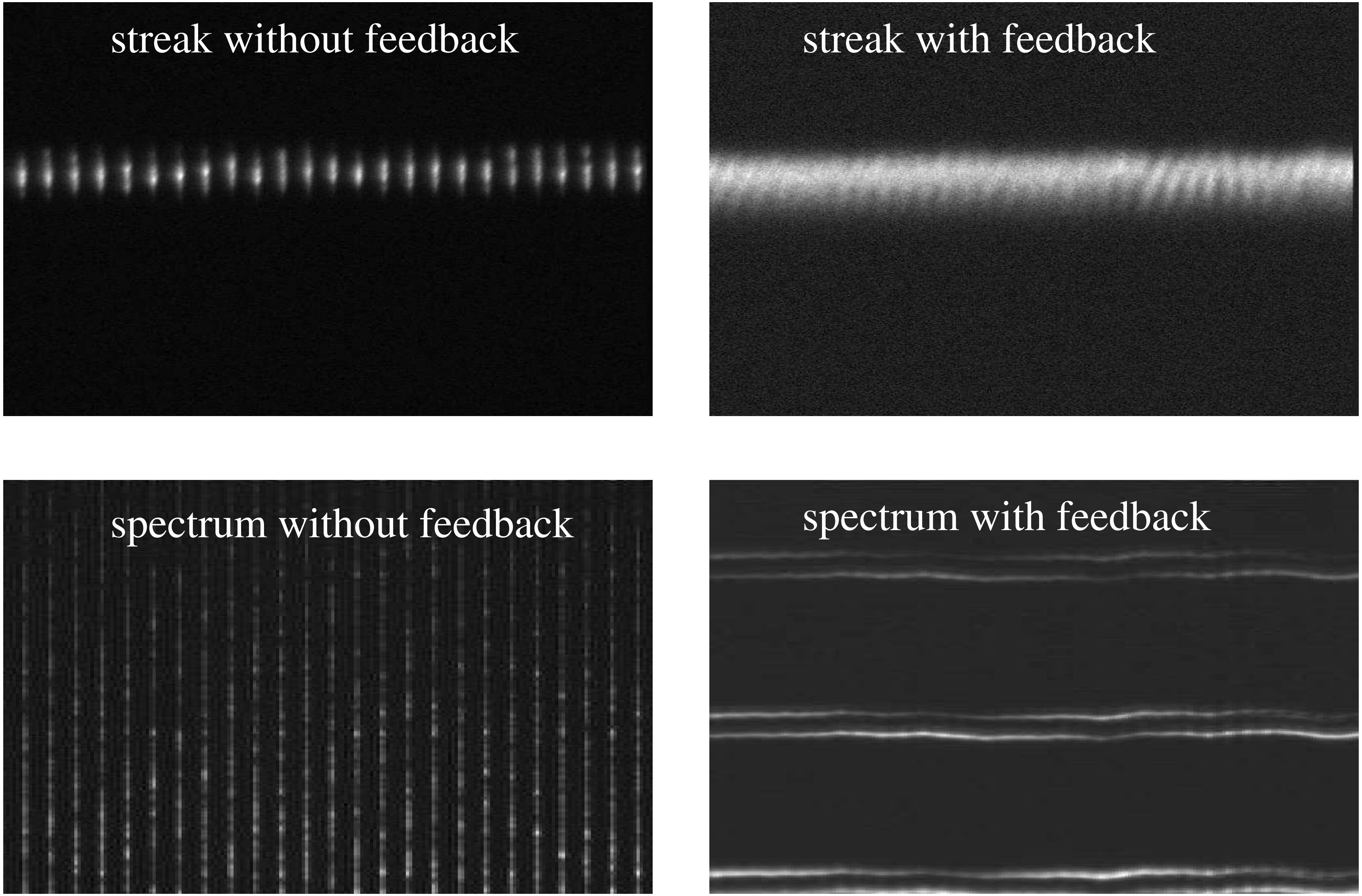
– consequences: "Stabilization" when detuned
→ spectral narrowing
→ suppression of the fast pulse substructures

– More general than FEL oscillators
→ applications in other systems where an amplified wave drifts inside a gain region

Perspectives:

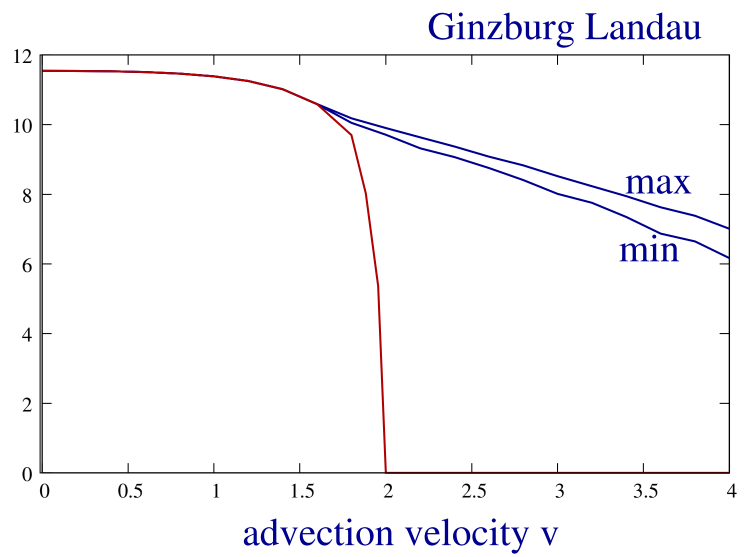
– Analytical criteria ?
→ local coupling (ex. :hydrodynamics): OK
→ global coupling coupling
specific to SR–FELs & classical lasers)
→ "In progress"...

– Influence of spurious reflexion on mirror rear–side?

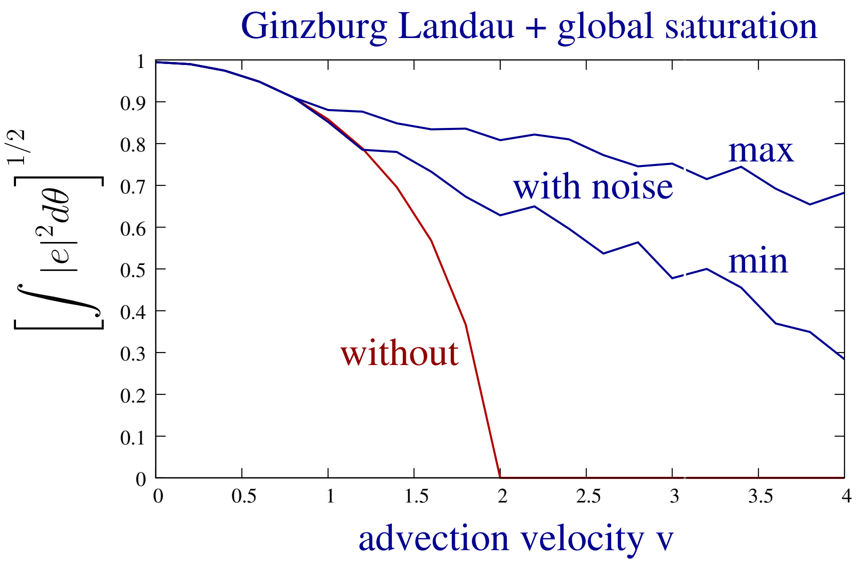

streak without feedback
streak with feedback
spectrum without feedback
spectrum with feedback

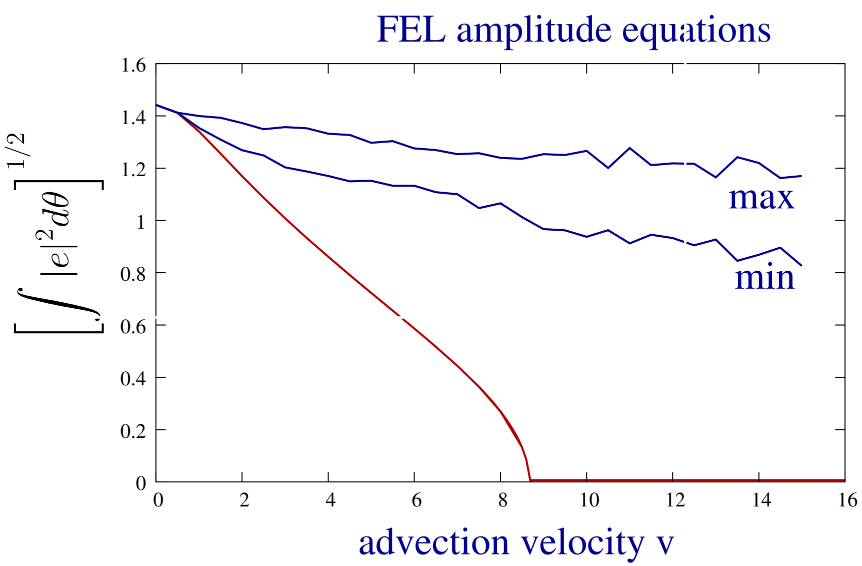
Analytical criteria for success ?

LOCAL saturation



GLOBAL saturation





Hypothesis: appearance of the non–trivial stationary solution

<–> transition from convective to absolute instability in a similar infinite system

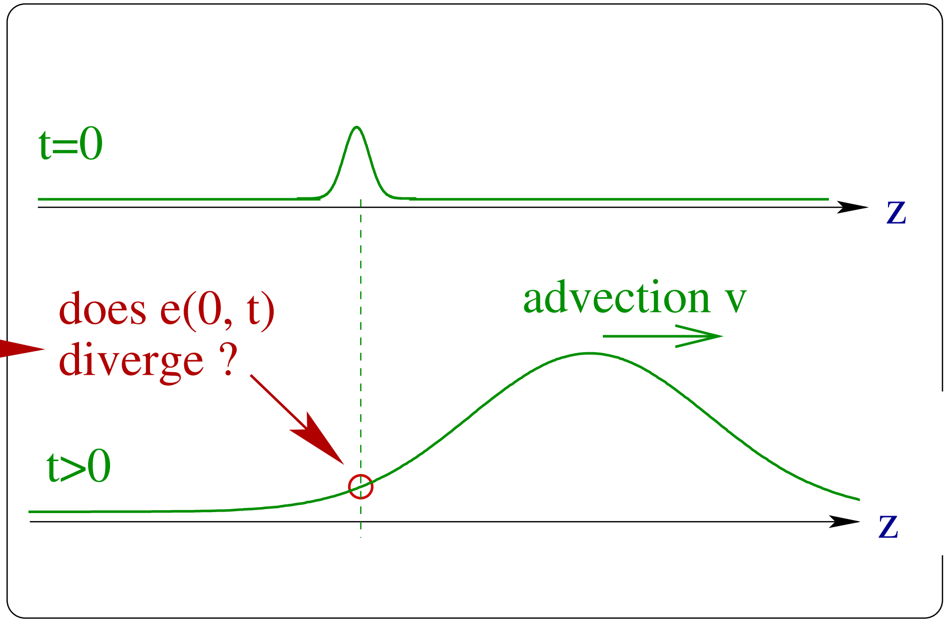
$$e_T + ve_z = Re + e_{zz} + \alpha e(z+\tau)$$

response to a Dirac in z=0 ?

$$e(0,t) = \boxed{\int_{-\infty}^{+\infty} e^{f(k)t} dk,}$$

with

$$f(k) = R - k^2 - ivk + \alpha e^{ik\tau}.$$



Method in systs. with nonlocality : *see in particular [Papoff & Zambrini, PRL94, 243903 (2005)]*

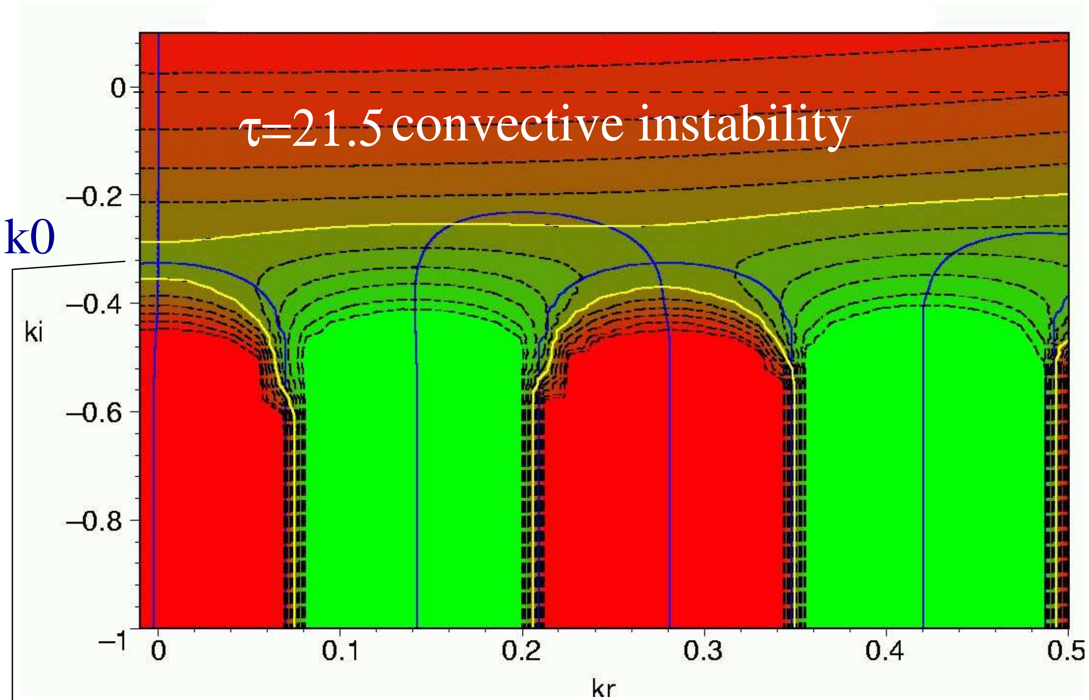
Basic concepts: see eg *[Sturrock, Phys. Rev. 112, 1488 (1958)]*

[Huerre and Monkewitz, Ann. Fluid Mech. 22, 473 (1990)]

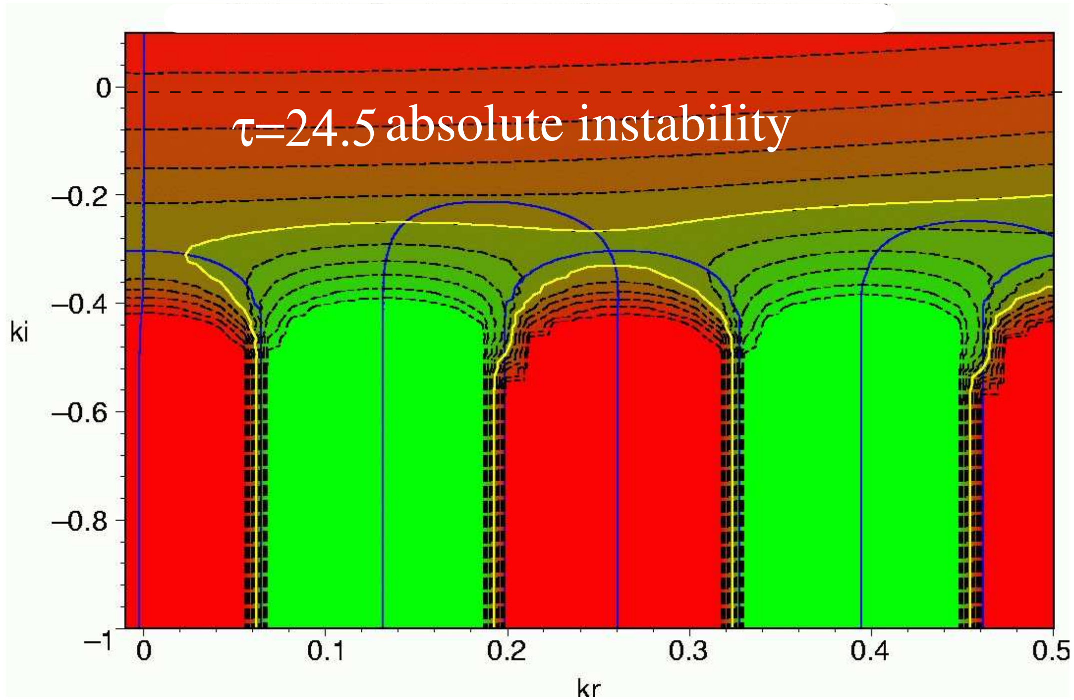
*[Tobias, Proctor, Knobloch Physica D113, 43 (1998)]

abs or cv <=> divergence or not of the integral —> saddle point method

real part of f(k)



real part of f(k)



k0

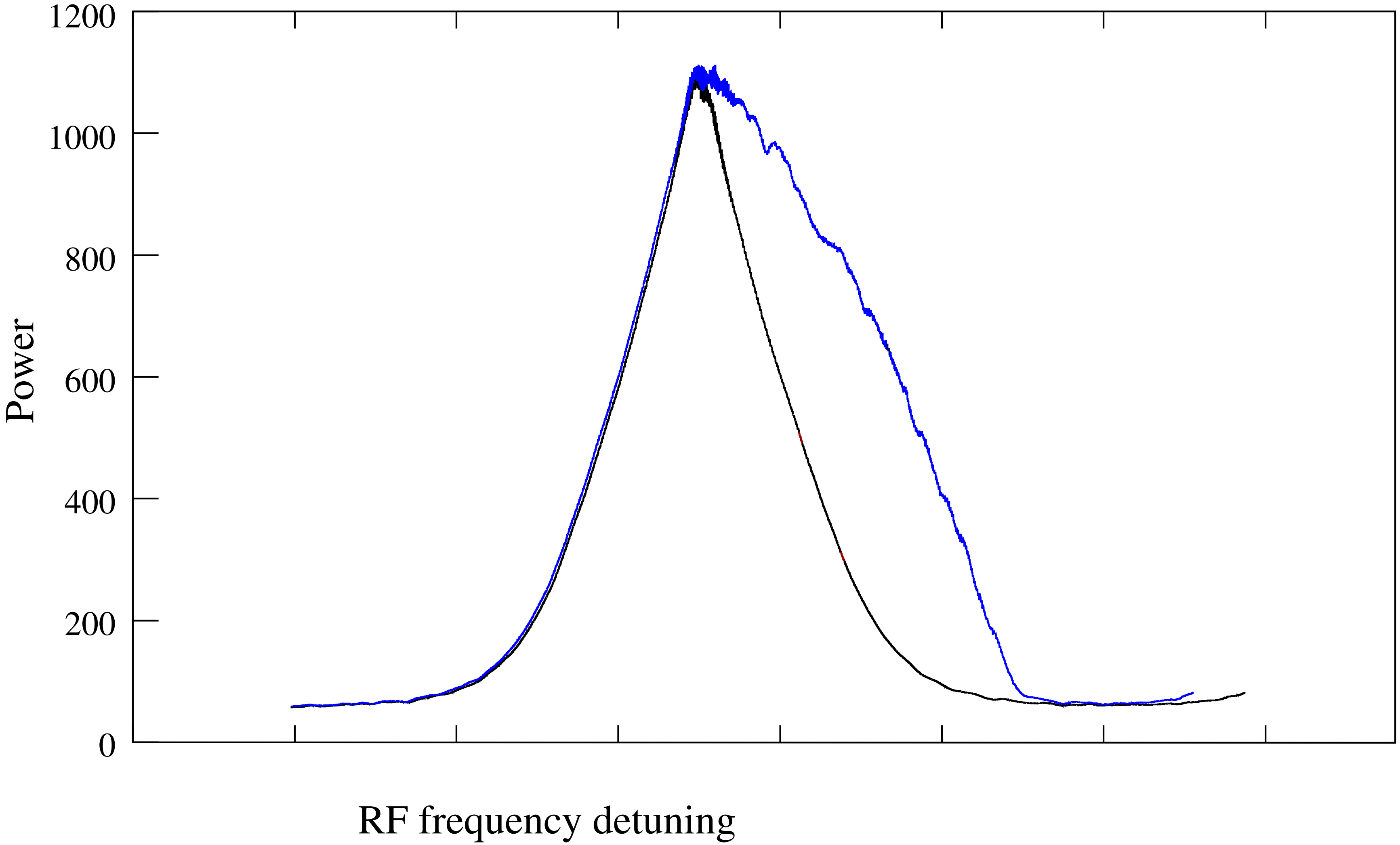
red>0
green<0

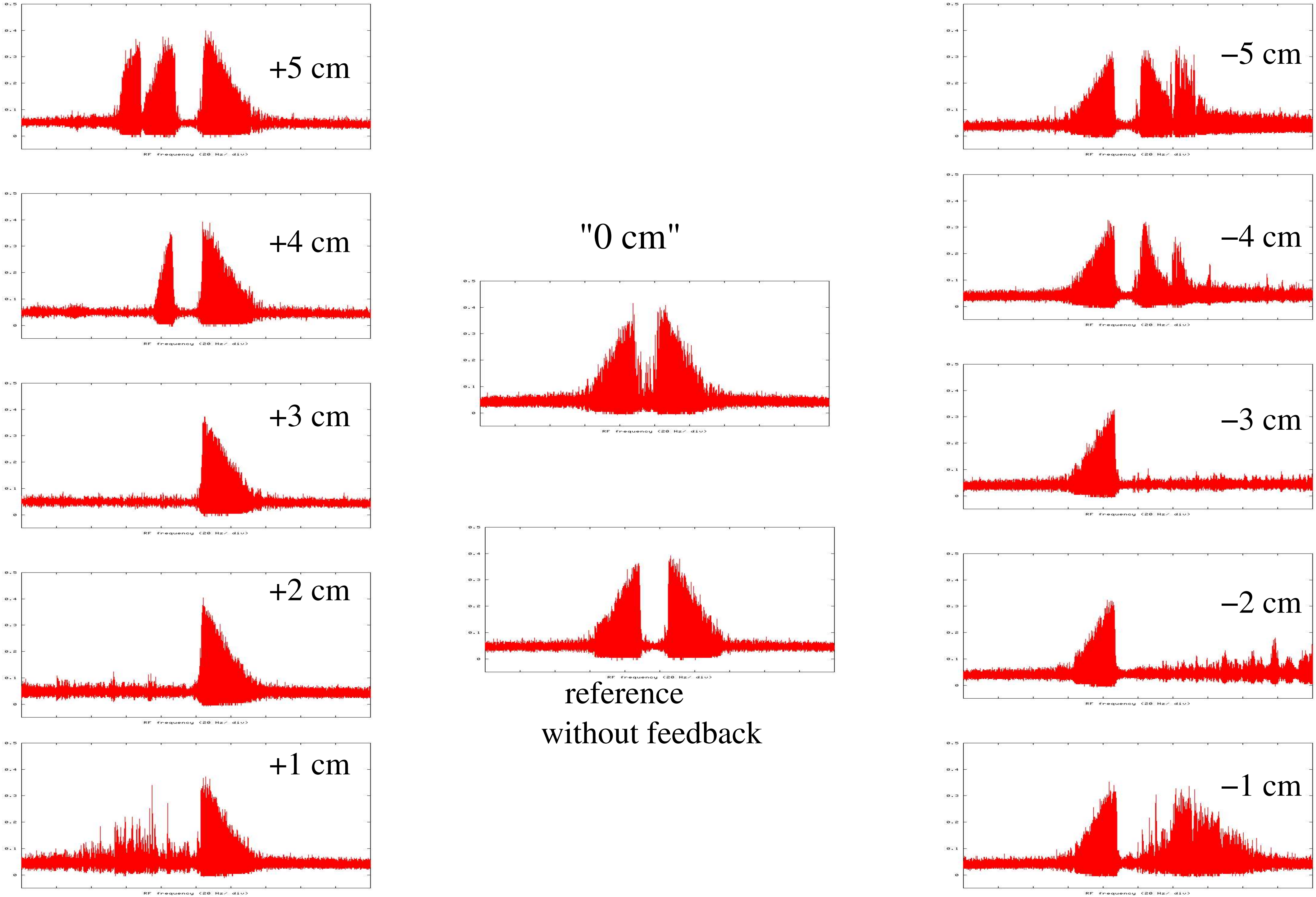
For the saddle in $k_0 = i\beta$:

$$\boxed{\begin{aligned} 2\beta + v - \alpha\tau e^{-\beta\tau} &= 0 \\ R + v\beta + \beta^2 + \alpha e^{-\beta\tau} &= 0 \end{aligned}}$$

$$\boxed{\alpha_b = \frac{e^{\beta_b\tau}}{\tau}(2\beta_b + v)}$$

with β_b solution of: $\tau\beta^2 + 2\beta(1 + \frac{\tau v}{2}) + v + R\tau = 0$


1200
1000
800
600
400
200
0
Power
RF frequency detuning


+5 cm
+4 cm
+3 cm
+2 cm
+1 cm
"0 cm"
reference
without feedback
−5 cm
−4 cm
−3 cm
−2 cm
−1 cm
RF frequency (20 Hz/ div)