Pulse-Splitting in Seeded Free Electron Lasers

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C. Szwaj, C. Bruni, M.E. Couprie

1008-FEL'10

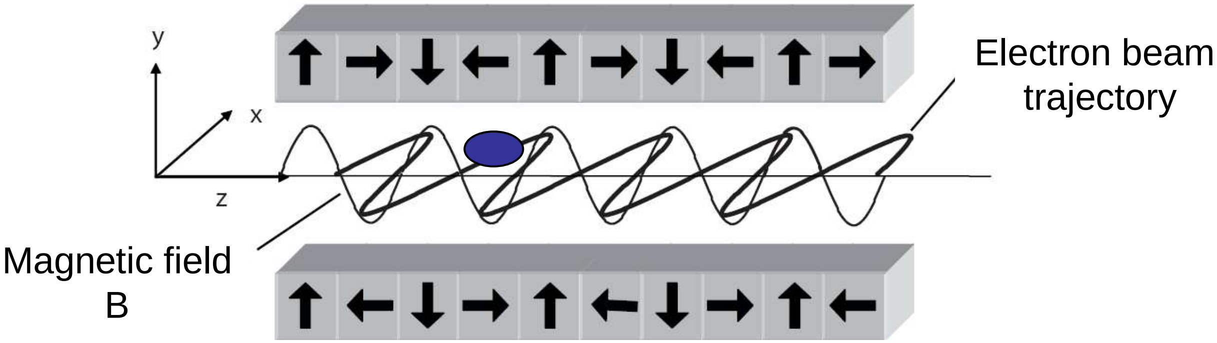
Introduction to seeded FELs

Principle of an FEL

- **Amplifier medium:**
  - Relativistic e- @ E ≈ MeV-GeV

    from accelerator (storage ring or LINAC)
  - Periodic magnetic field

    generated in an undulator

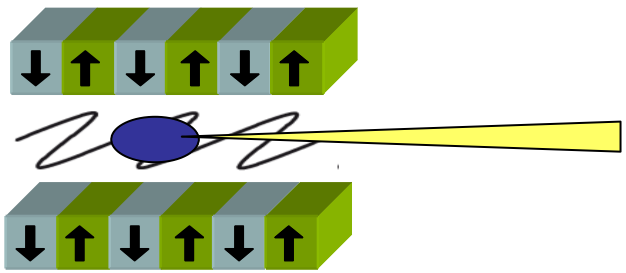


Introduction to seeded FELs

Principle of an FEL

- **Optical radiation:**
  - Spontaneous emission:

    Synchrotron radiation



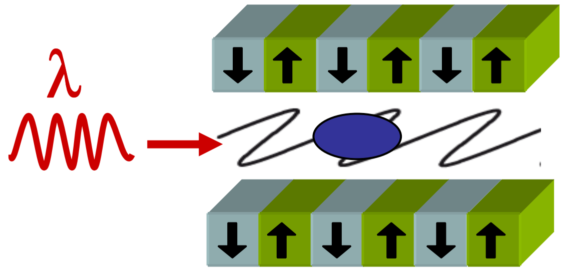
Resonant wavelength:

$$\lambda = \frac{\lambda_u}{2n\gamma^2}(1 + \frac{K^2}{2})$$

  - External source or **seed**:

    Conventionnal laser, etc..

Seeded FEL



Introduction to seeded FELs

Advantages of seeded FELs

- **Injection of a coherent seed** enables:

  L.H. Yu, Phys. Rev. A 44 (1991).

  - Reduction of the saturation length
  - Higher temporal coherence
  - Higher shot to shot stability
  - Shorter and controlled pulse duration
  - Stronger nonlinear harmonic generation
  - More efficient cascading configurations

- **Seed sources:**
  - Conventional lasers: **$\lambda > 250$ nm**
  - High order Harmonics Generated in gas (HHG): **$270 > \lambda > 1$ nm**

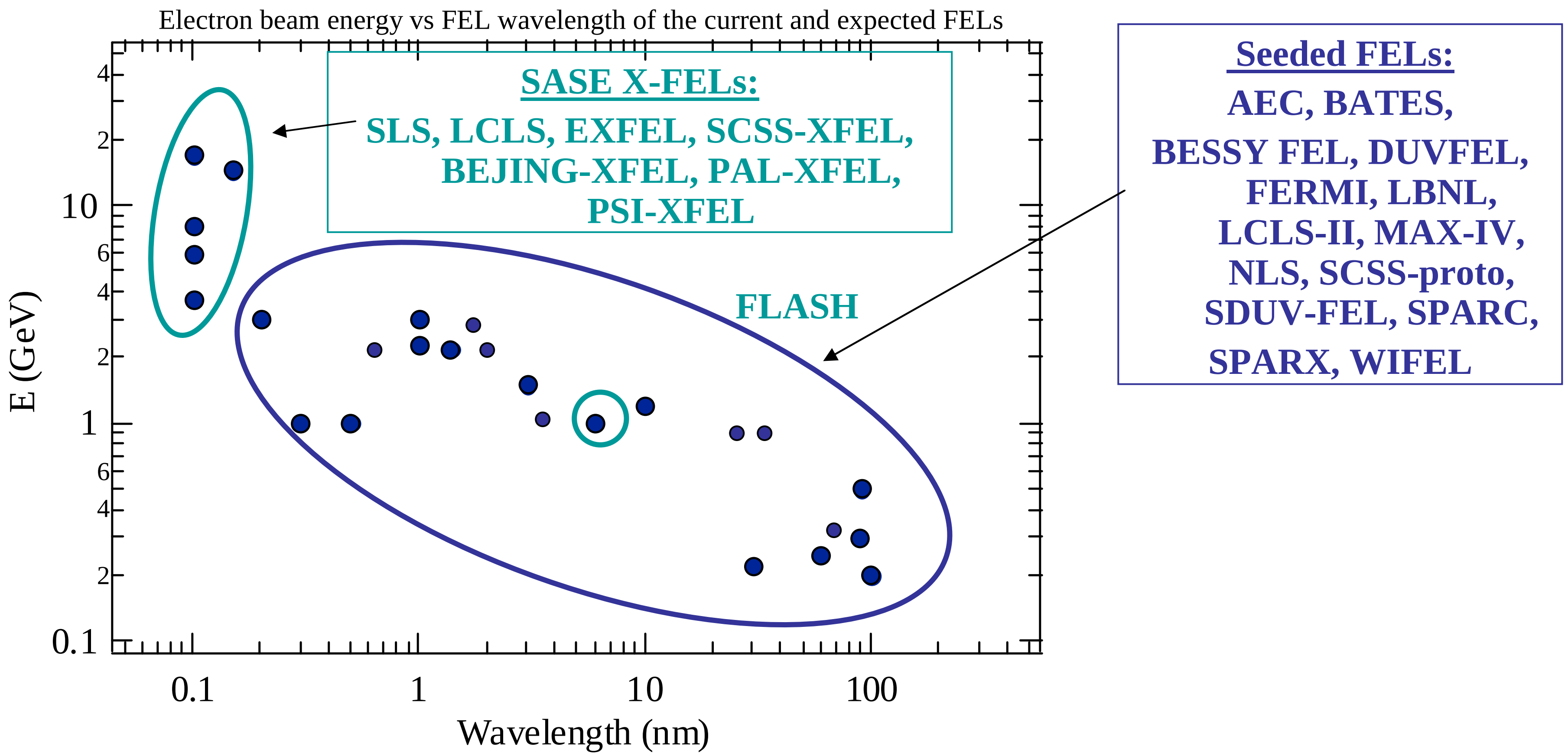
D. Garzella et al., NIMA 528, 502 (2004).

M.E. Couprie et al., NIMA 528, 507 (2004).

→ **HHG + HGHG : Coherent compact FELs at very short wavelengths**

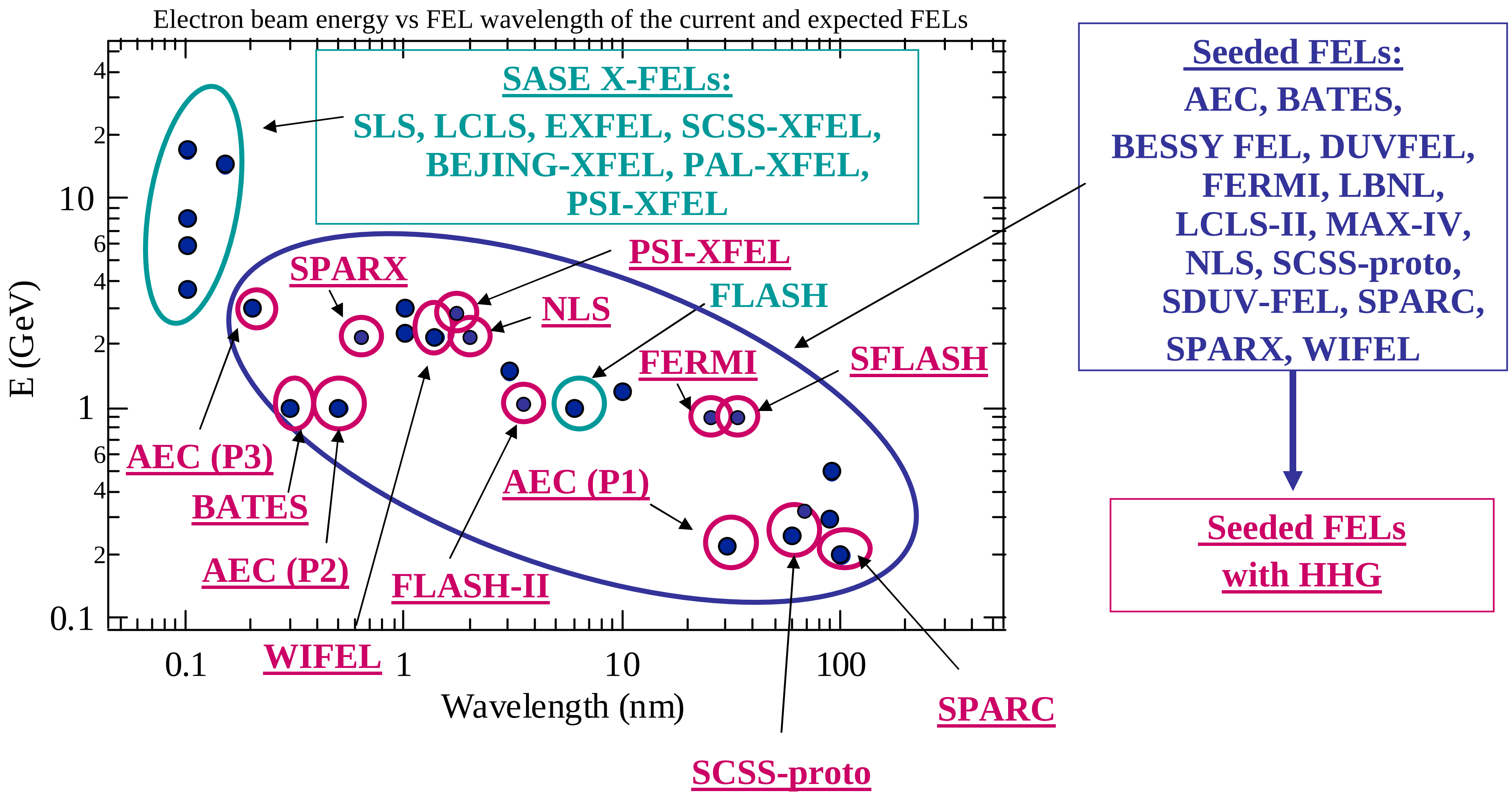
Introduction to seeded FELs

Seeded FELs around the world



Introduction to seeded FELs

Seeded FELs around the world



The ARC-EN-CIEL project

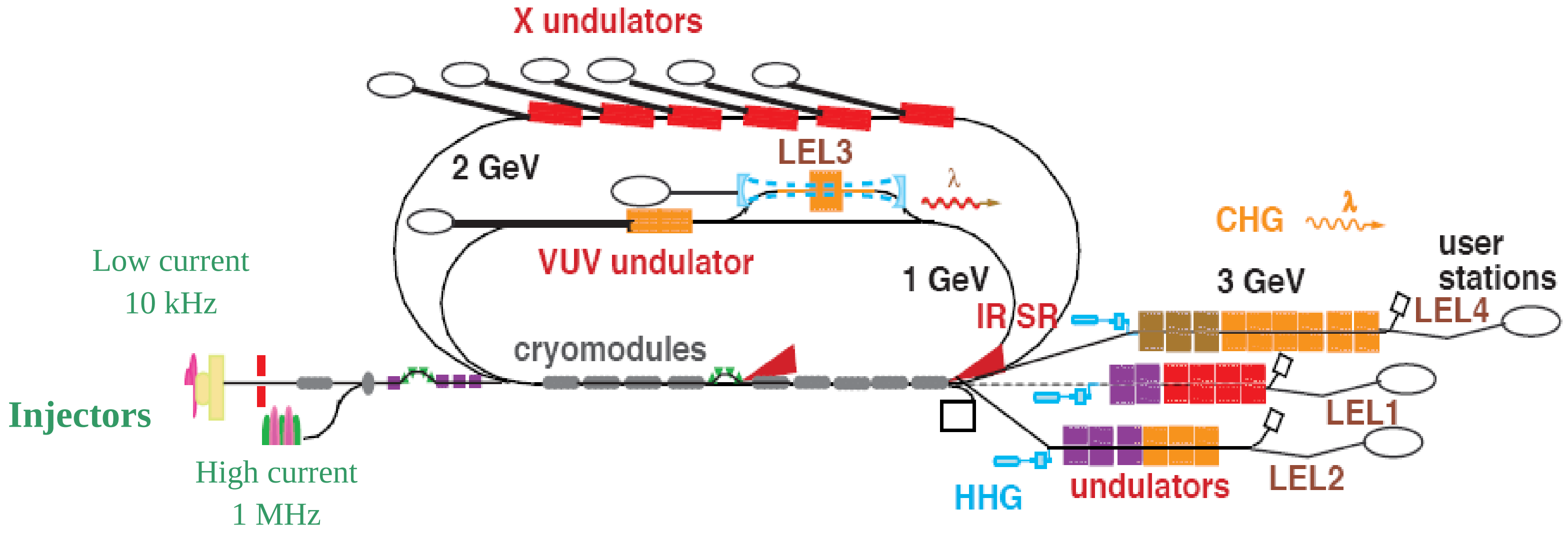
Introduction

http://arcenciel.synchrotron.fr/ArcEnCiel

The ARC-EN-CIEL project

Light sources

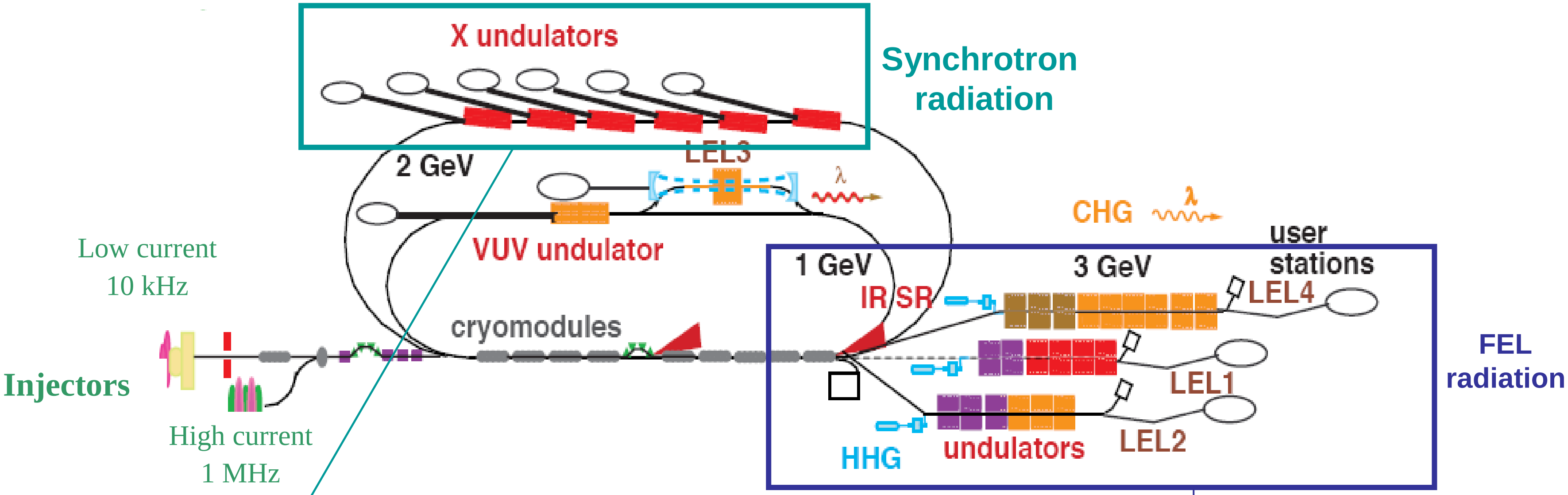
http://arcenciel.synchrotron.fr/ArcEnCiel



- **4th generation light source:**
  - Synchrotron radiation from undulators (IR to X-rays):
    U20 and U30 (planar + helical)
  - 4 Free Electron Lasers:
    3 seeded HGHG ($\lambda \rightarrow$ 0.3 nm) + 1 oscillator (VUV)

The ARC-EN-CIEL project

Writting of the CDR



Simulations with SRW

http://www.esrf.eu/Accelerators/Groups/InsertionDevices/Software/SRW

Simulations with PERSEO

http://www.perseo.enea.it

…!!

Simulation of a VUV seeded FEL

Parameters for AEC – FEL1

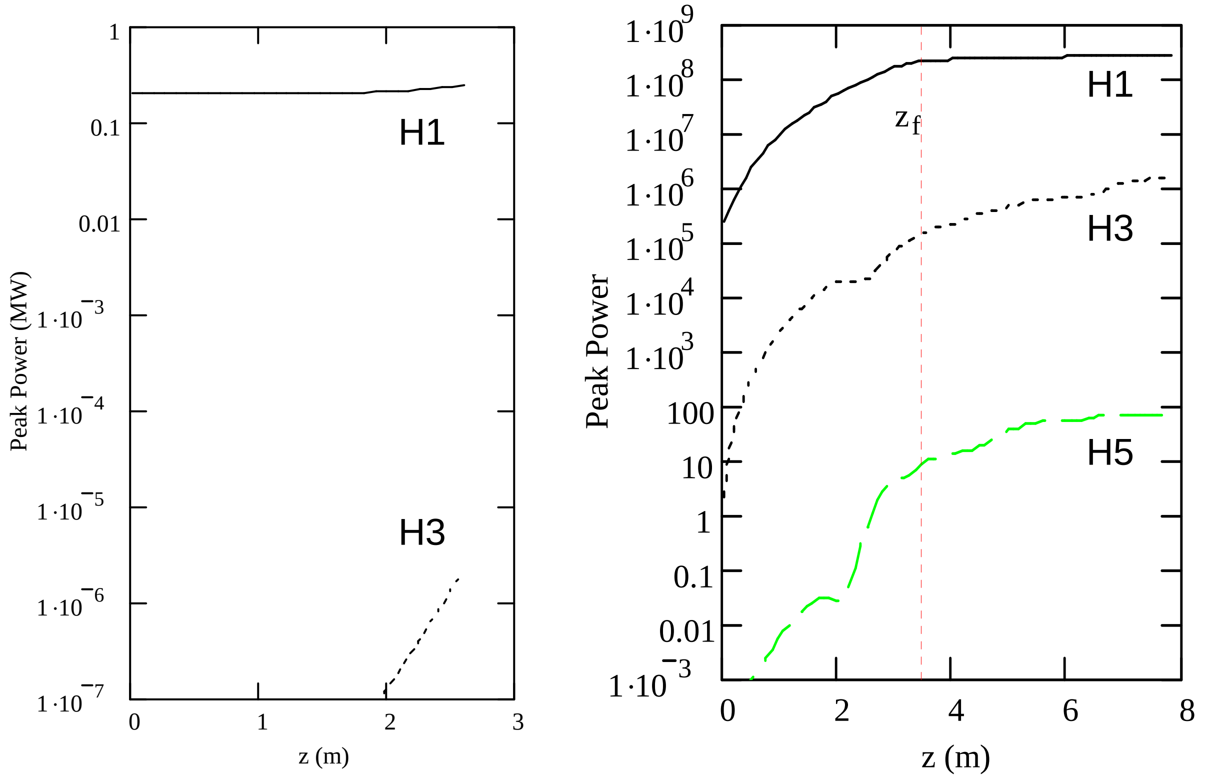
- Electron beam:
  - E=220 MeV, I=300A, σ_z=450 fs-rms, ε=1.2.π.mm.mrad
- Seed:
  - 114 nm
  - 200 kW in 150 fs-fwhm
- Undulators:
  - Modulator: 100 periods of 26 mm
  - Dispersive section: R_{56}=1.5 μm
  - Radiator: 260 periods of 30 mm
- **Final wavelength = 114 nm**

Simulation of a VUV seeded FEL

Performances of AEC – FEL1

Peak power evolution in the:

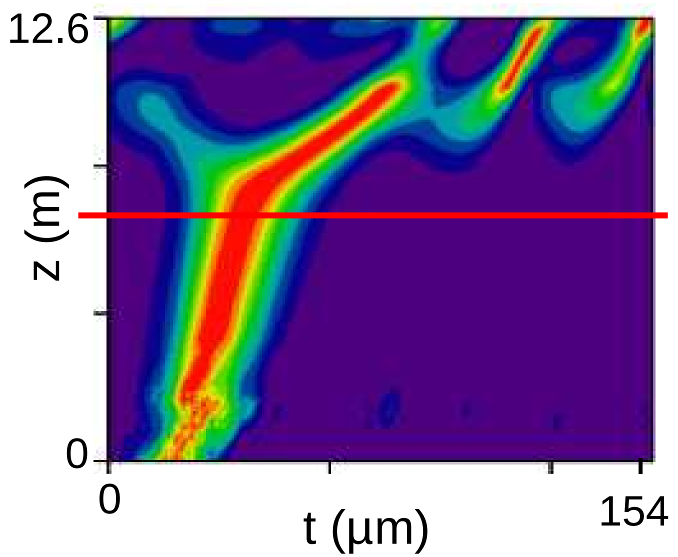
modulator — radiator



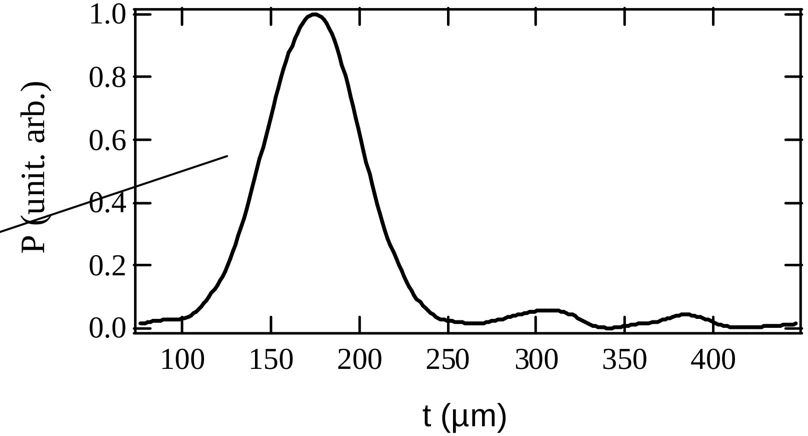
Simulation of a VUV seeded FEL

« Performances » of AEC – FEL1

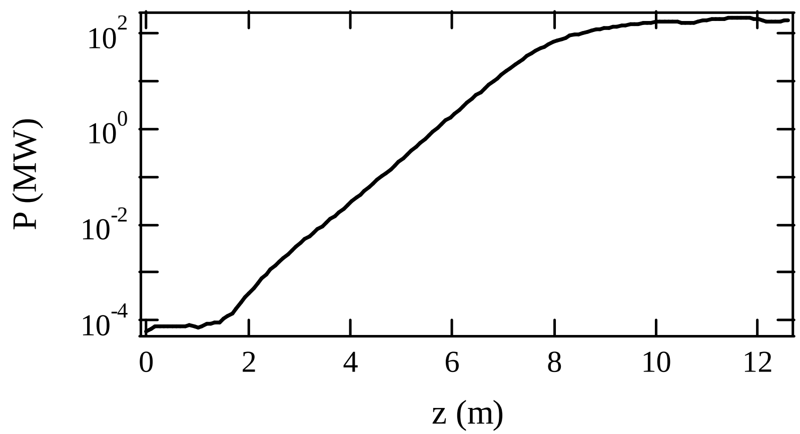
Looking at spatio-temporal diagrams



Longitudinal profile



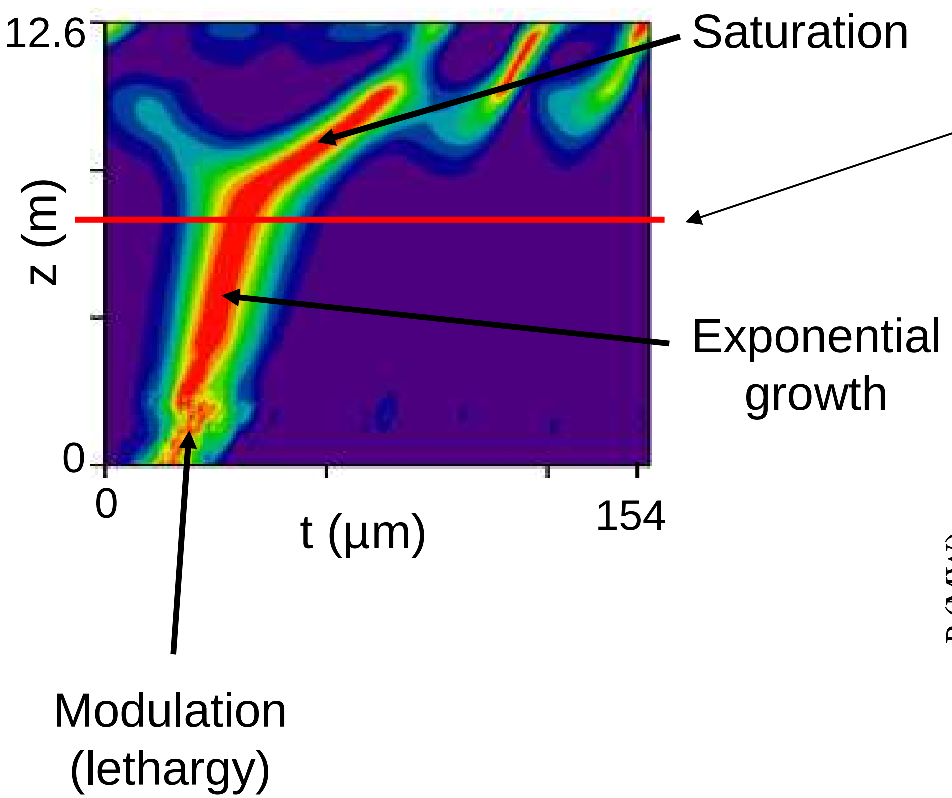
Peak power

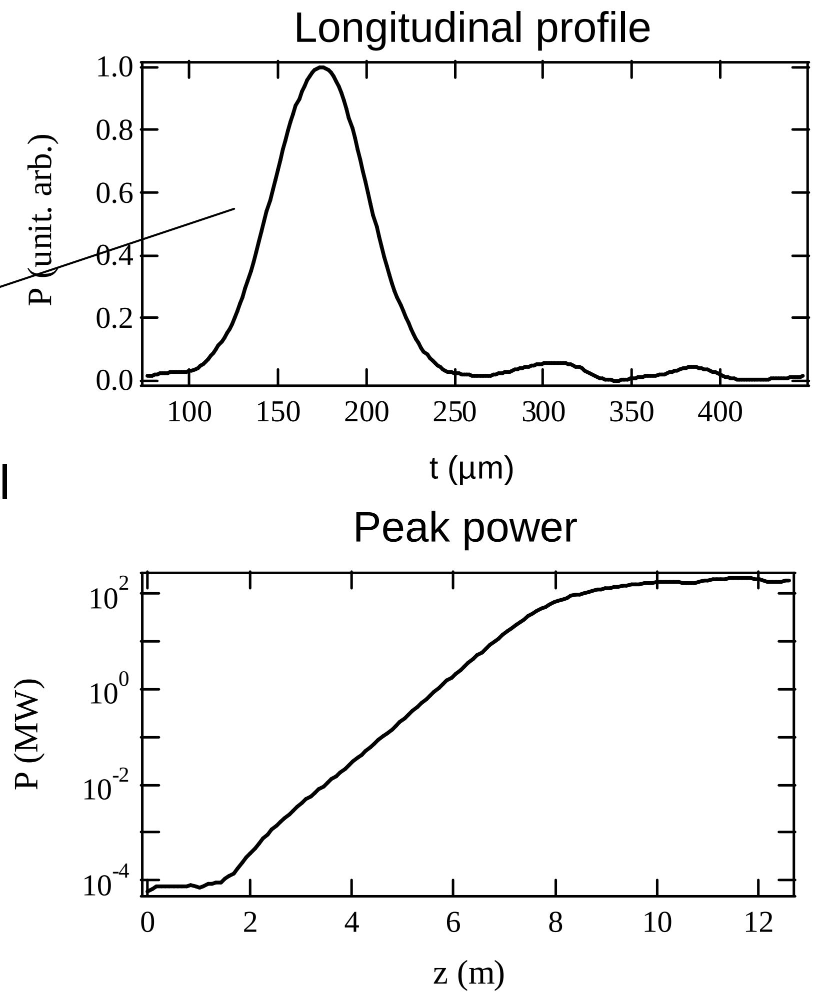


Simulation of a VUV seeded FEL

« Performances » of AEC – FEL1

Looking at spatio-temporal diagrams



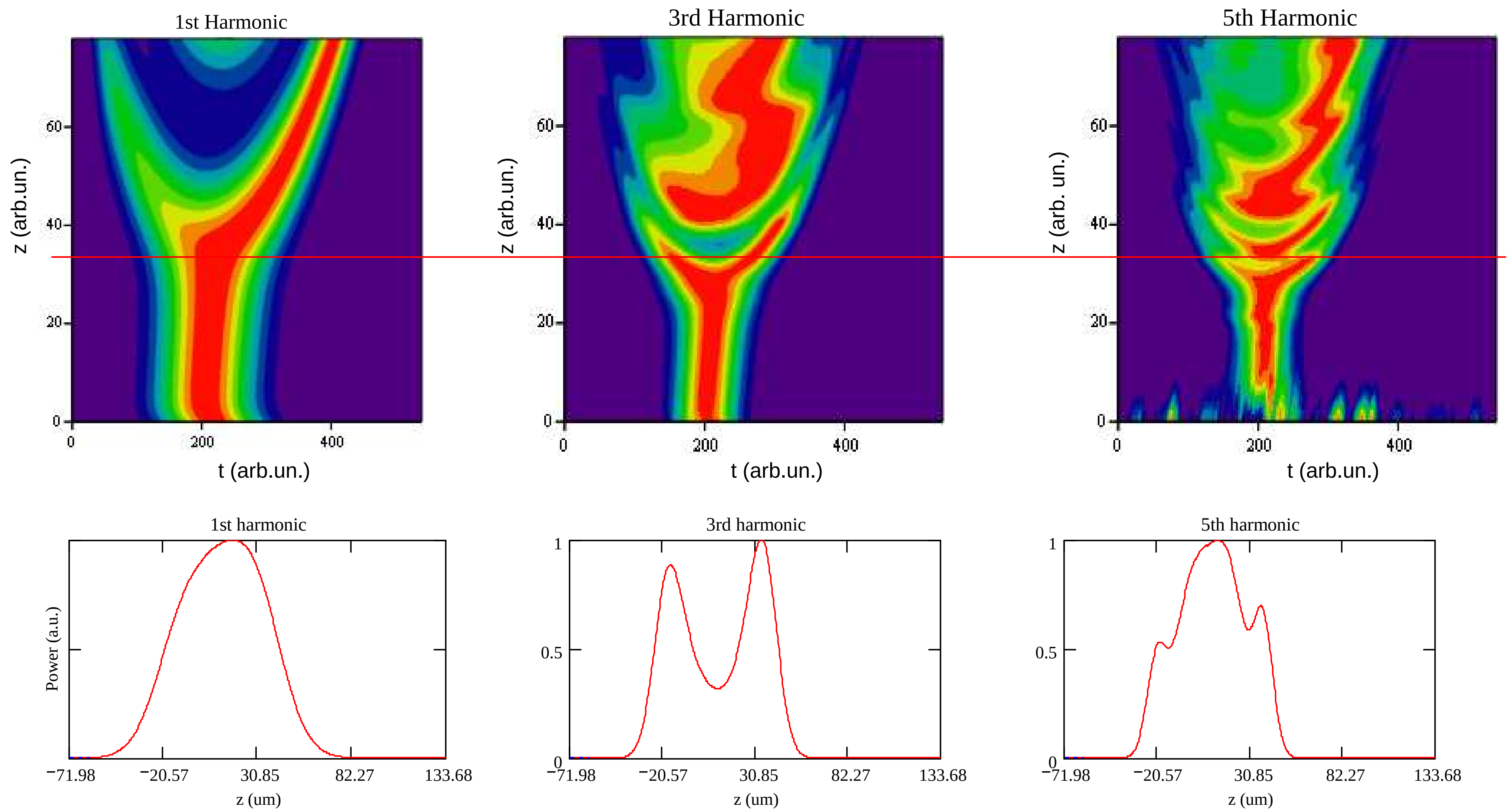


Simulation of a VUV seeded FEL

« Performances » of AEC – FEL1

Simulation of a VUV seeded FEL

« Performances » of AEC – FEL1



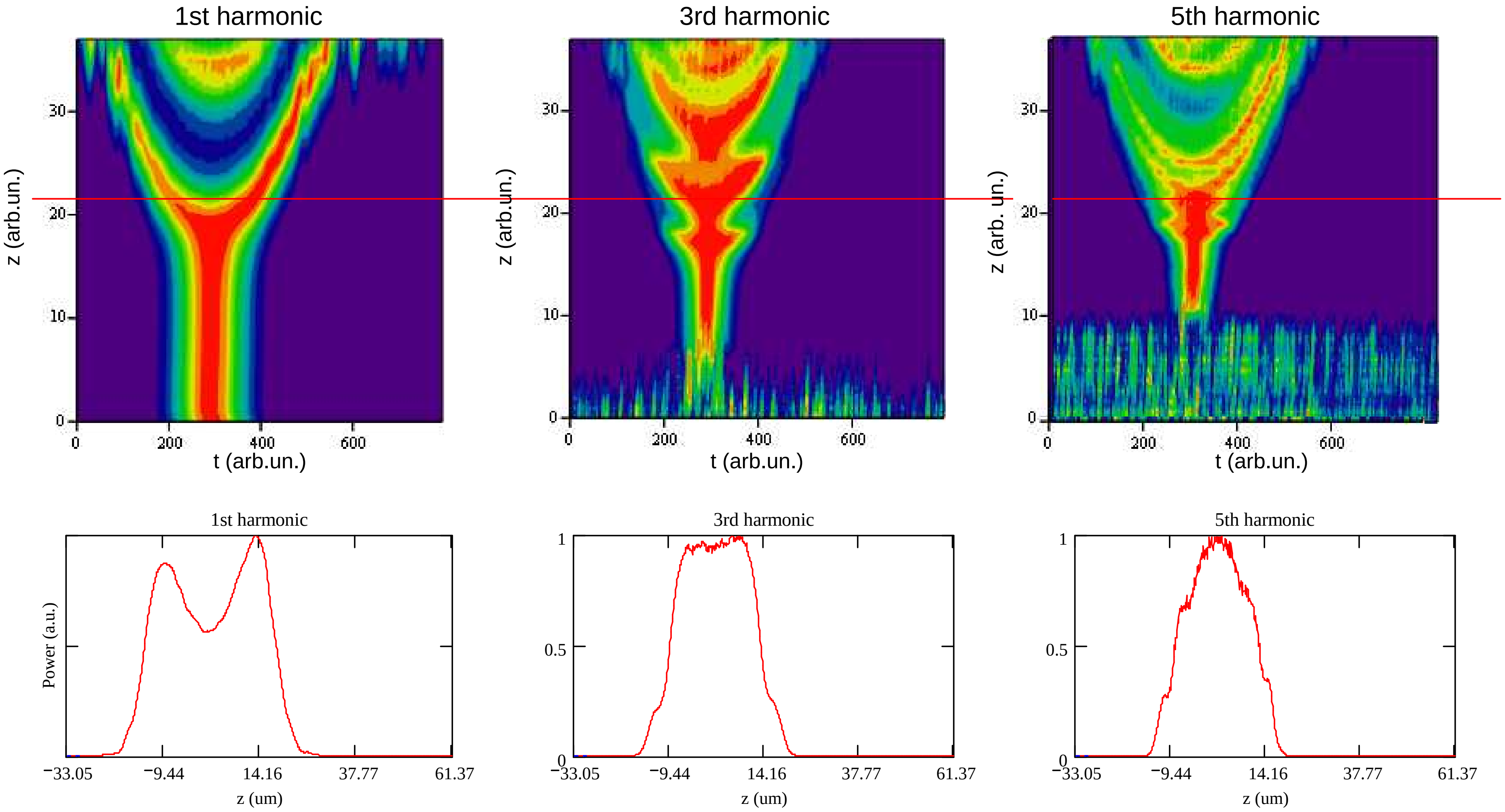
Simulation of a XUV seeded FEL

Parameters of AEC – FEL2

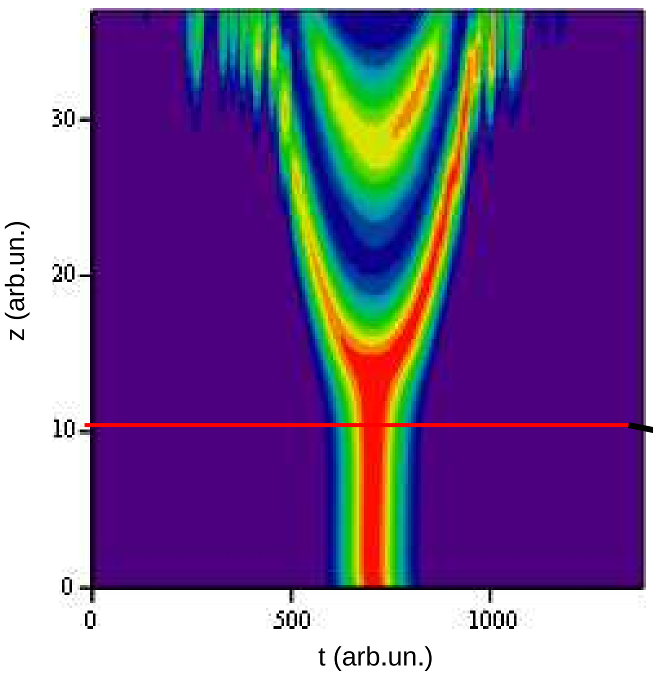
- Electron beam:
  - E=1 GeV, I=1500A, σ_z=200 fs-rms, ε=1.2.π.mm.mrad
- Seed:
  - 8.9 nm
  - 30 kW in 50 fs-fwhm
- Undulators:
  - Modulator: 200 periods of 26 mm
  - Dispersive section: R_{56}=1.5 μm
  - Radiator: 500 periods of 15 mm
- **Final wavelength = 8.9 nm**

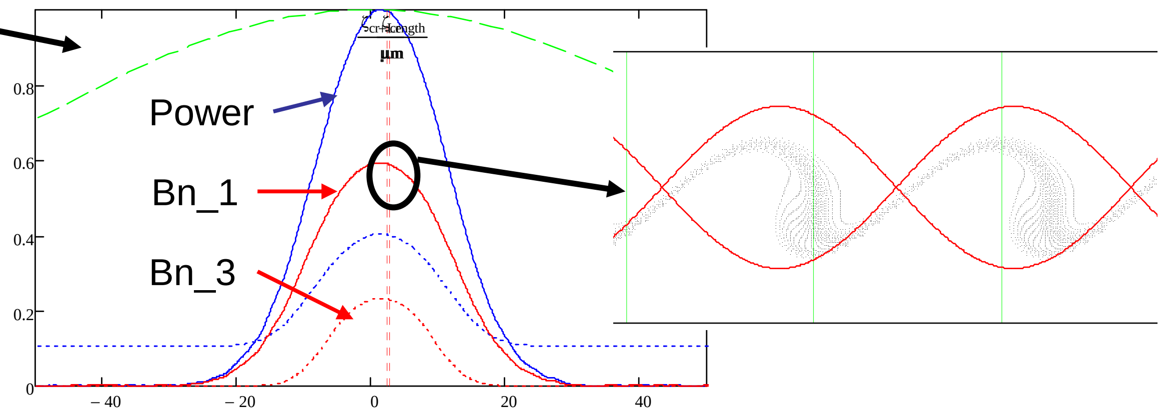
Simulation of a XUV seeded FEL

« Performances » of AEC – FEL2



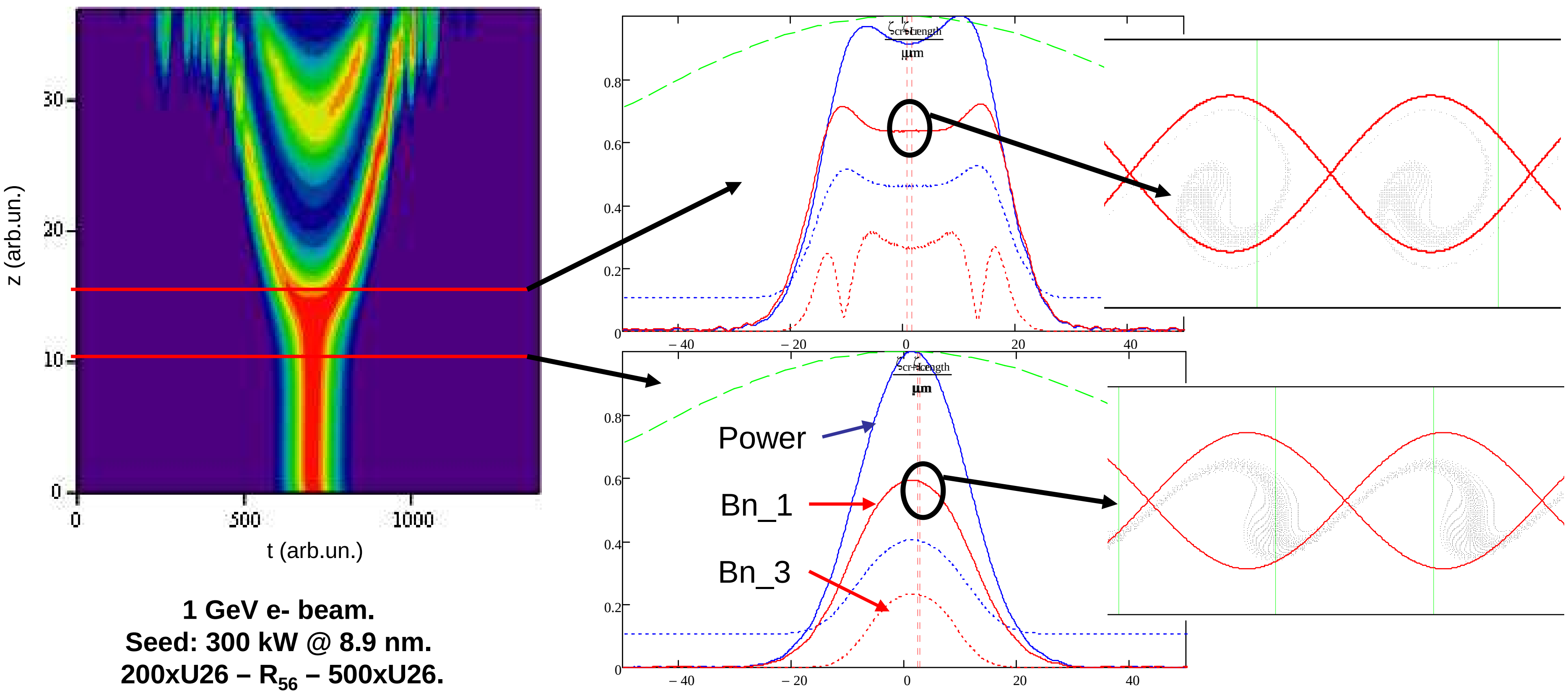
Pulse splitting and overbunching





1 GeV e- beam.
Seed: 300 kW @ 8.9 nm.
200xU26 – R_{56} – 500xU26.

Pulse splitting and overbunching



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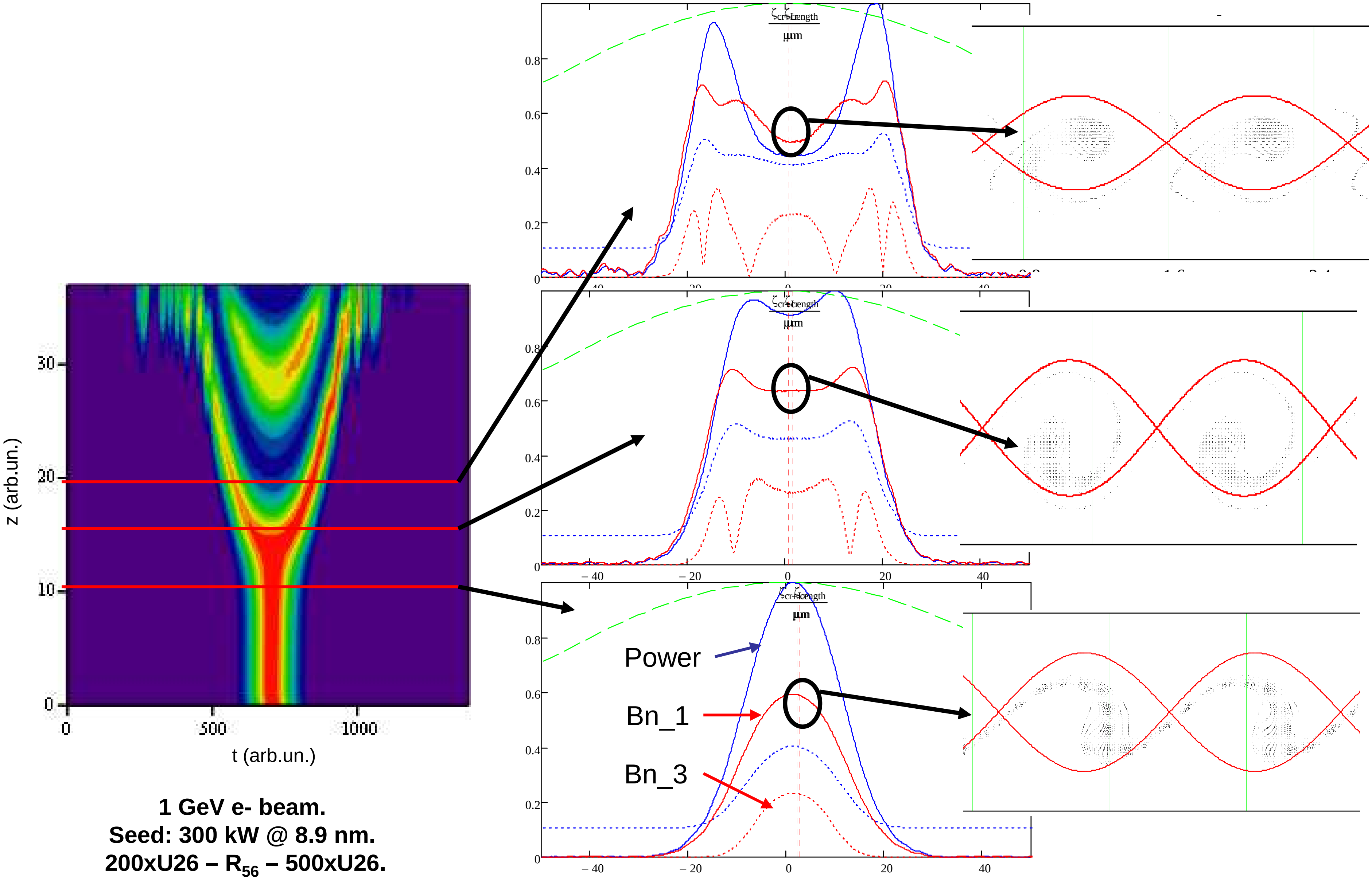

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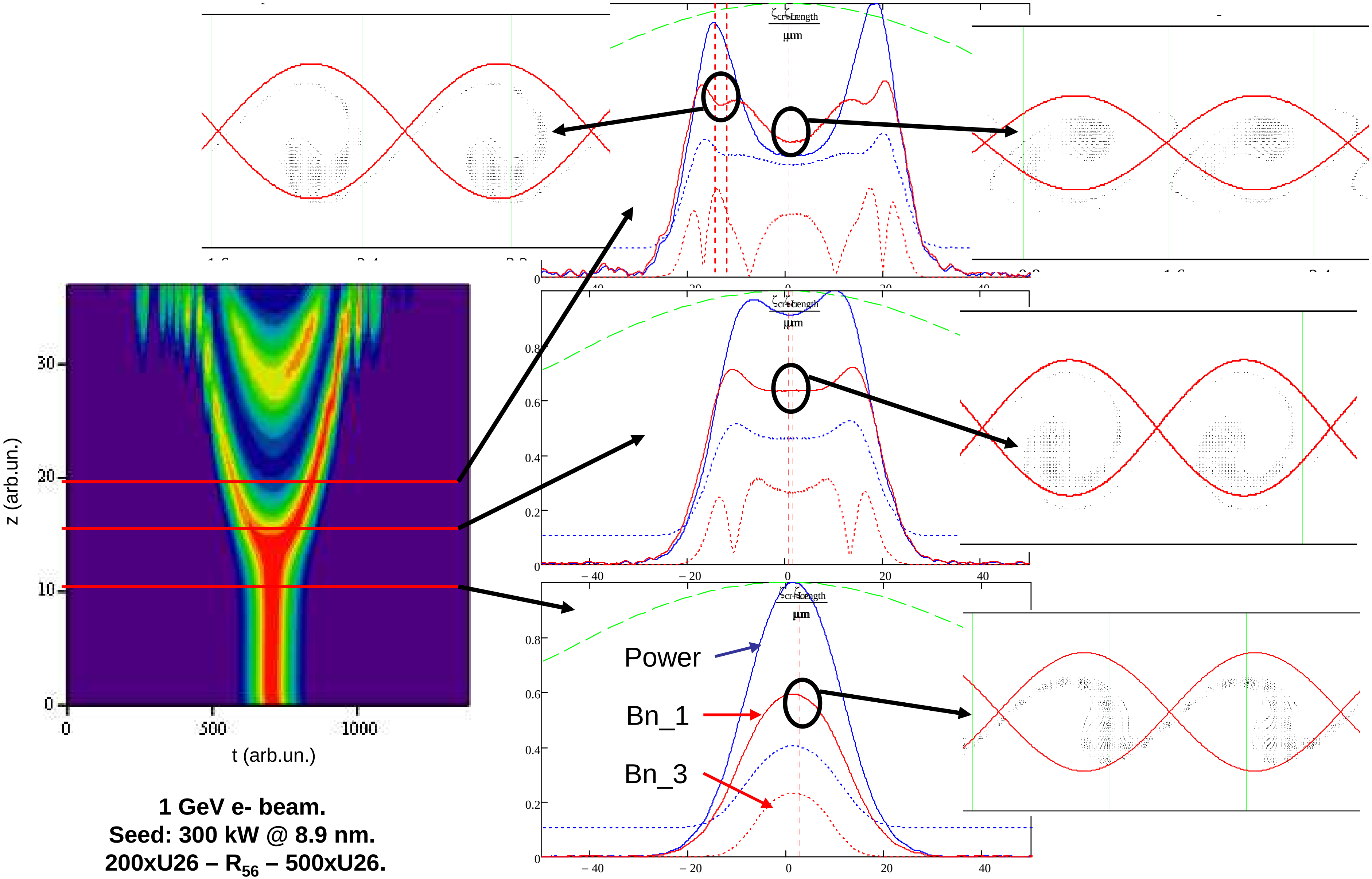
Pulse splitting and overbunching



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Seed: 300 kW @ 8.9 nm.
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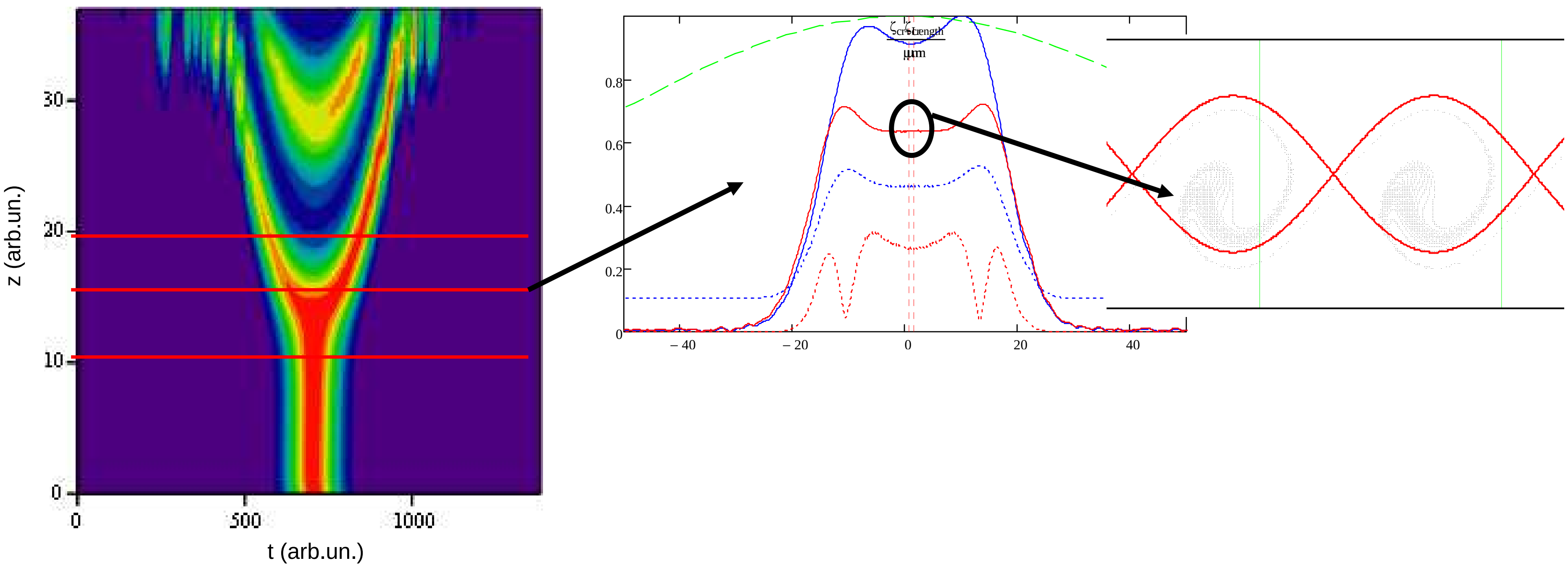
Simulation of a XUV seeded FEL

Pulse splitting and overbunching

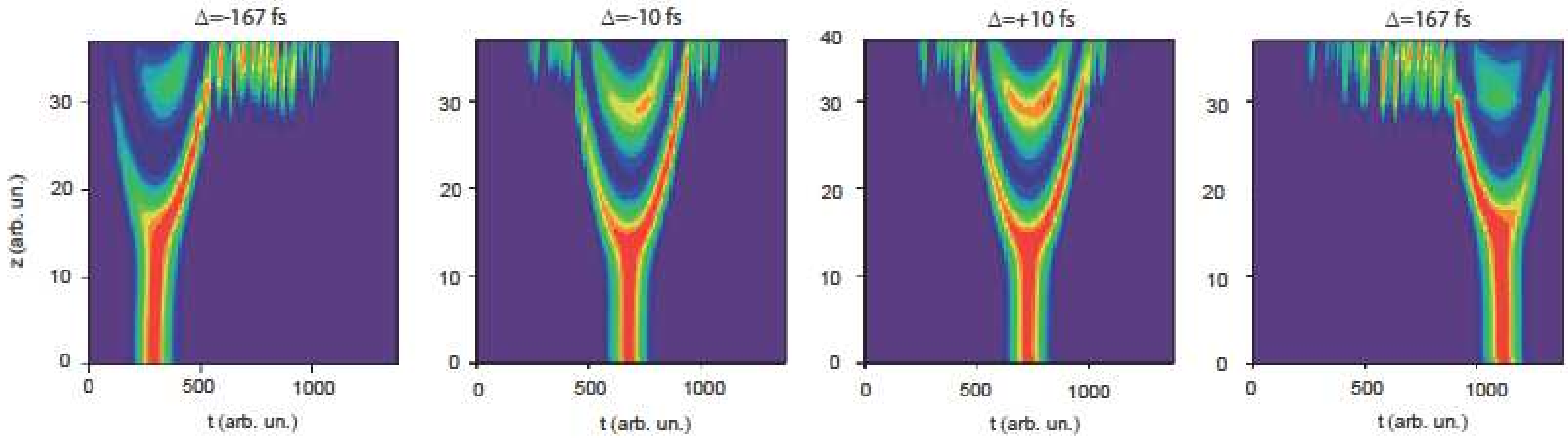


Pulse splitting is related to <u>local overbunching</u>

Pulse splitting dependencies

Pulse splitting dependencies

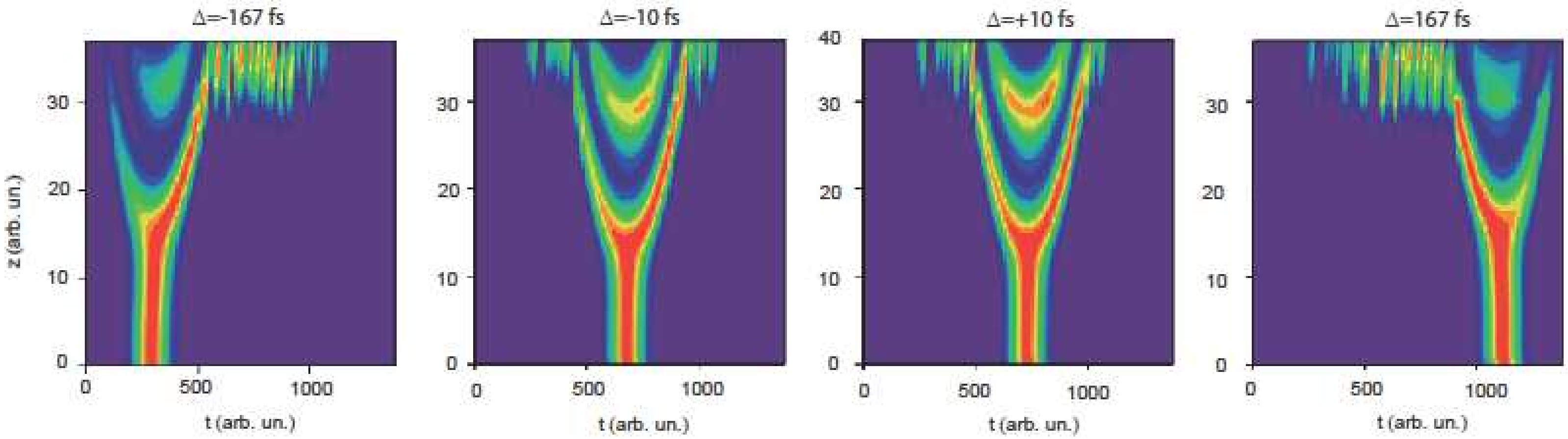
Vs synchronization



1 GeV e- beam. Seed: 300 kW @ 8.9 nm. 200xU26 – R_{56} – 500xU26.

Pulse splitting dependencies

Vs synchronization

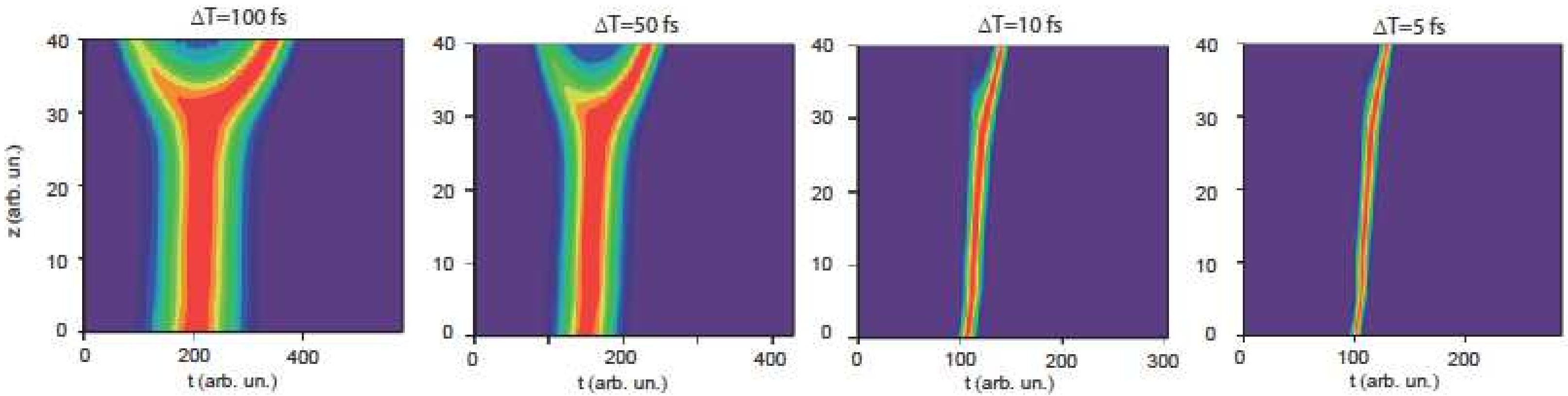


1 GeV e- beam. Seed: 300 kW @ 8.9 nm. 200xU26 – R_{56} – 500xU26.

→ **Pulse splitting <u>follows the gain medium</u>**

Pulse splitting dependencies

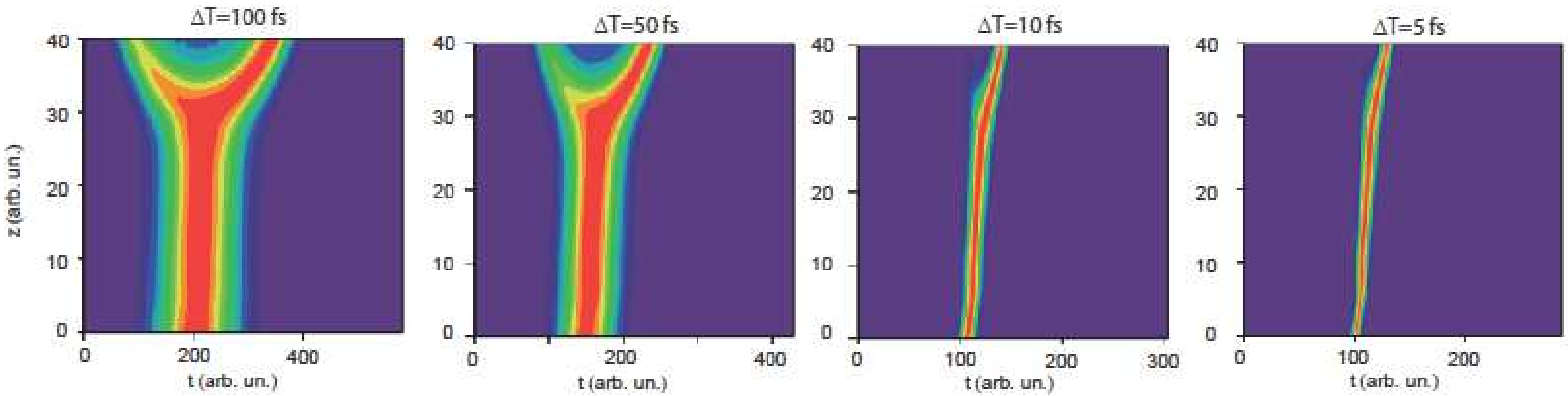
Vs pulse duration



1 GeV e- beam. Seed: 50 kW @ 14 nm. 700xU26.

Pulse splitting dependencies

Vs pulse duration



1 GeV e- beam. Seed: 50 kW @ 14 nm. 700xU26.

→ **Pulse splitting occurrence depends in seed duration**

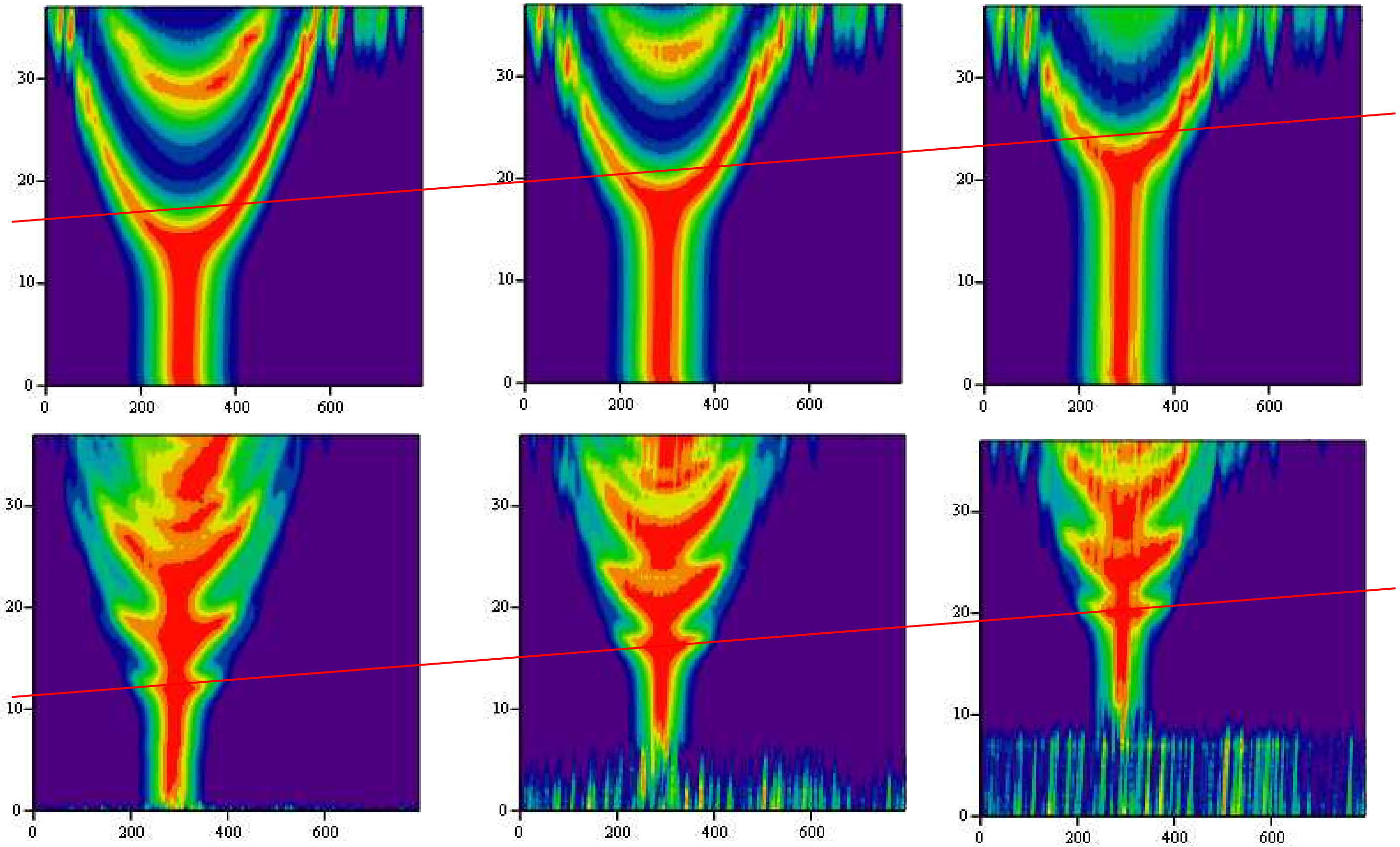
Pulse splitting dependencies

Vs power

300 kW | 30 kW | 3 kW

1st harmonic

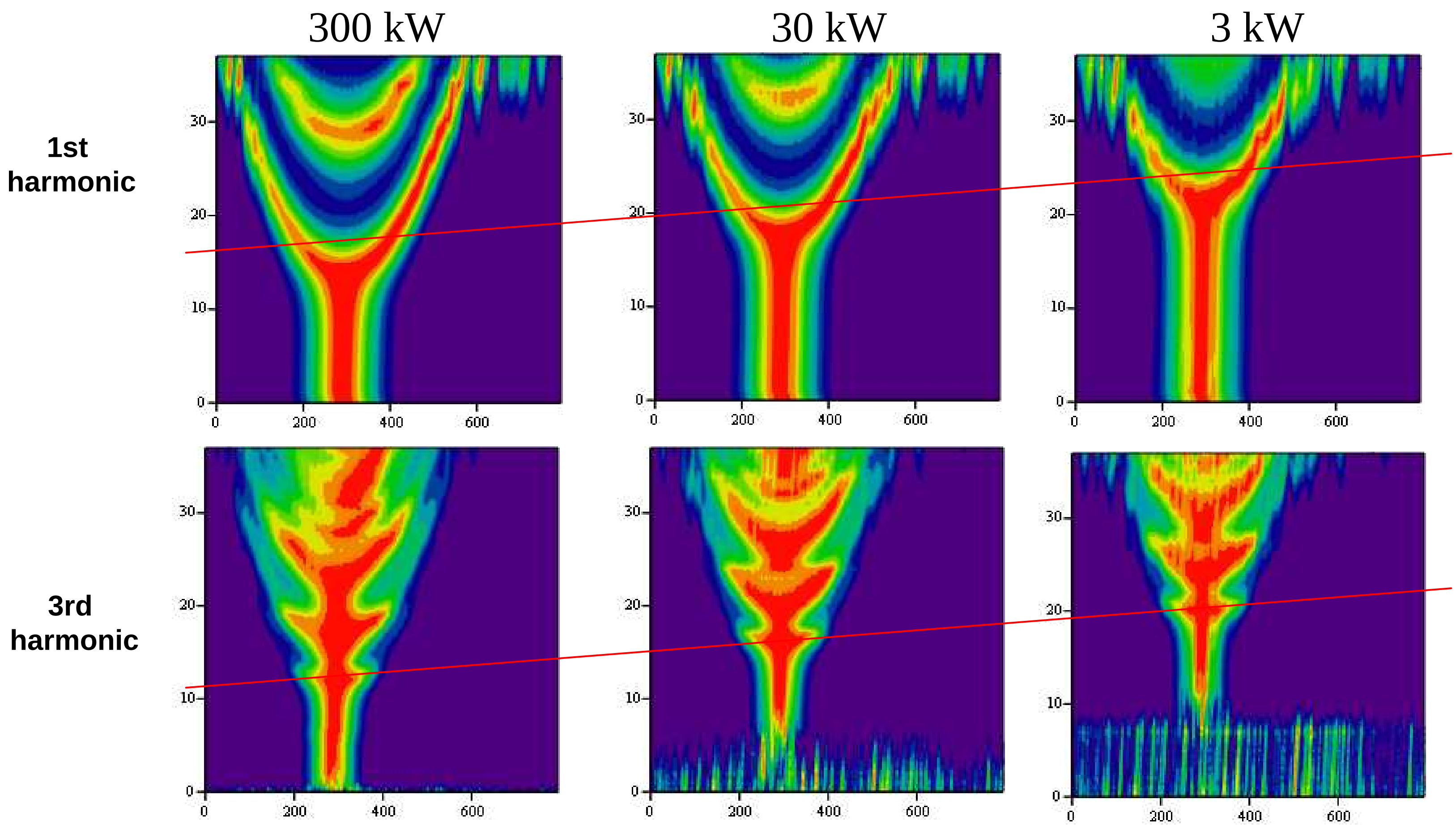
3rd harmonic



1 GeV e- beam. Seed @ 8.9 nm. 200xU26 – R_{56} – 500xU26

Pulse splitting dependencies

Vs power



→ **Pulse splitting occurrence does not depend in power**

Pulse splitting in seeded FELs

Intermediate conclusion

- Simulation of VUV and XUV seeded FELS (ARC-EN-CIEL):

  → Observation of a pulse splitting

- Study of the double pulse behavior:
  - Related to local overbunching / follows gain medium
  - Related to seed pulse duration
  - Not due to excessive seeding power

  → Requires a better understanding

→ **Start over from FEL fundamental equations**

Modeling of a seeded FEL

The 1-D Colson-Bonifacio model

W.B. Colson, Phys. Lett. A 59 (1976)
B. Bonifacio et al., PRA 40 (1989)

Modeling of a seeded FEL

The 1-D Colson-Bonifacio model

- **Modeling of the e- beam:**
  - N_e particles in the phase space (Φ,p):
    - Φ_j: relative phase
    - p_j: relative normalized energy
  - Particles distribution:
    - Φ_j: uniform distribution within $[-\pi;\pi]$
    - p_j: normal distribution centred at 0 with standard deviation σ_γ.

Modeling of a seeded FEL

The 1-D Colson-Bonifacio model

- **Modeling of the e- beam:**
  - N_e particles in the phase space (Φ,p)
  - Particles distribution

- **Modeling of the radiation:**
  - Radiation potentiel vector A(z,t)

- **Dimensionless coordinates:**
  - z: along the undulator in slippage length units
  - t: along the electron bunch in cooperation length units

Modeling of a seeded FEL

The 1-D Colson-Bonifacio model

W.B. Colson, Phys. Lett. A 59 (1976)
B. Bonifacio et al., PRA 40 (1989)

- **FEL equations:**

$$\frac{\partial \phi_j}{\partial z} = p_j$$

$$\frac{\partial p_j}{\partial z} = -\left[A(z,t)\ e^{i\phi_j} + c.c.\right]$$

Evolution of the particles in the phase space (Φ_j, p_j)

$$\left(\frac{\partial}{\partial z} + \frac{\partial}{\partial t}\right) A(z,t) = \chi(t)\ b(z,t)$$

Propagation of the field A in the electronic medium

Modeling of a seeded FEL

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Evolution of the particles in the phase space (Φ_j,p_j)

$$\left(\frac{\partial}{\partial z} + \frac{\partial}{\partial t}\right) A(z,t) = \boxed{\chi(t)\; b(z,t)}$$

Propagation of the field A in the electronic medium

Source term

Modeling of a seeded FEL

The 1-D Colson-Bonifacio model

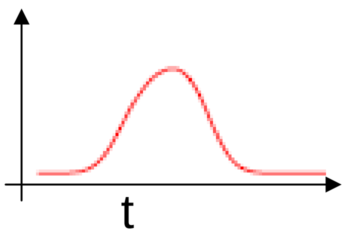
W.B. Colson, Phys. Lett. A 59 (1976)
B. Bonifacio et al., PRA 40 (1989)

- **FEL equations:**

$$\chi(t)\ b(z,t)$$

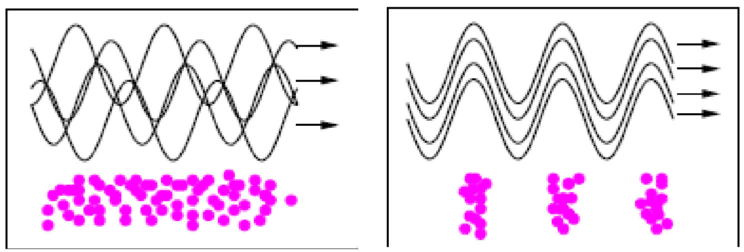
Source term

Macroscopic electronic density



Bunching coefficient

$$b(z,t) = \frac{1}{N_e}\sum e^{-i\phi_j}$$



Modeling of a seeded FEL

Numerical tool

N. Joly

- **Integration of the FEL equations:**
  - Description of the particles dynamics
  - Description of the evolution of the radiation pulse
  - Analysis of the **spatio-temporal regimes** of the seeded FEL with dimensionless parameters

Analysis of the spatiotemporal regimes

A few dimensionless parameters

B. Bonifacio et al., PRA 40 (1989)

- « Slippage parameter »:

$$S_e = \frac{\text{slippage length}}{\text{e}-\ \text{bunch length}}$$

- « Superradiant parameter »:

$$K = \frac{\text{cooperation length}}{\text{e}-\ \text{bunch length}}$$

Analysis of the spatiotemporal regimes

New tools for seeded FELs

- **Radiation potentiel vector:**

$$A(z=0,t) = A_0 \Rightarrow A(z=0,t) = A_0 e^{-\frac{1}{2}\left(\frac{t}{\sigma_t}\right)^2}$$

shot noise

seed

- Additional dimensionless **« seed » parameter**:

$$S_{seed} = \frac{\text{slippage length}}{\text{seed pulse length}}$$

Analysis of the spatiotemporal regimes

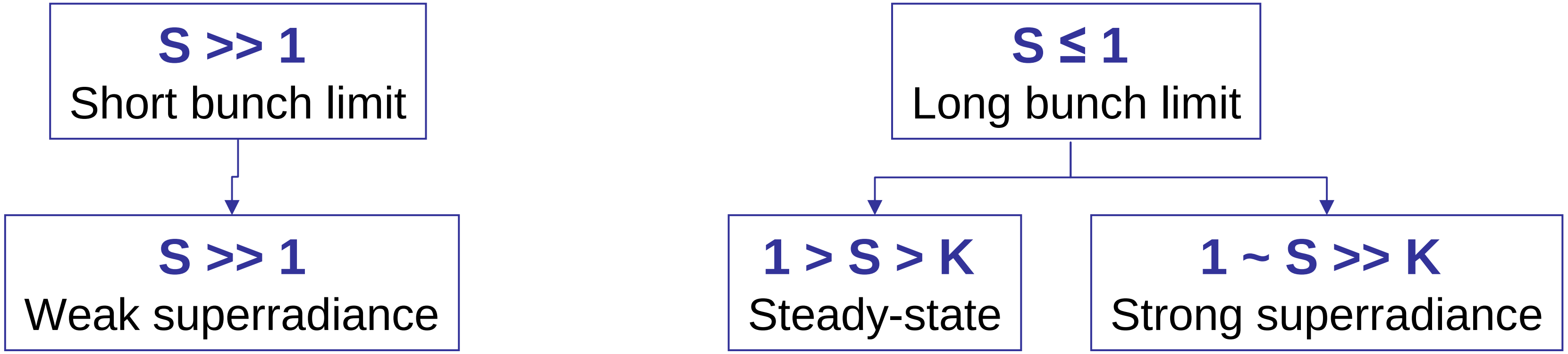
« Initial » regimes

B. Bonifacio et al., PRA 40 (1989)

Analysis of the spatiotemporal regimes

« Initial » regimes

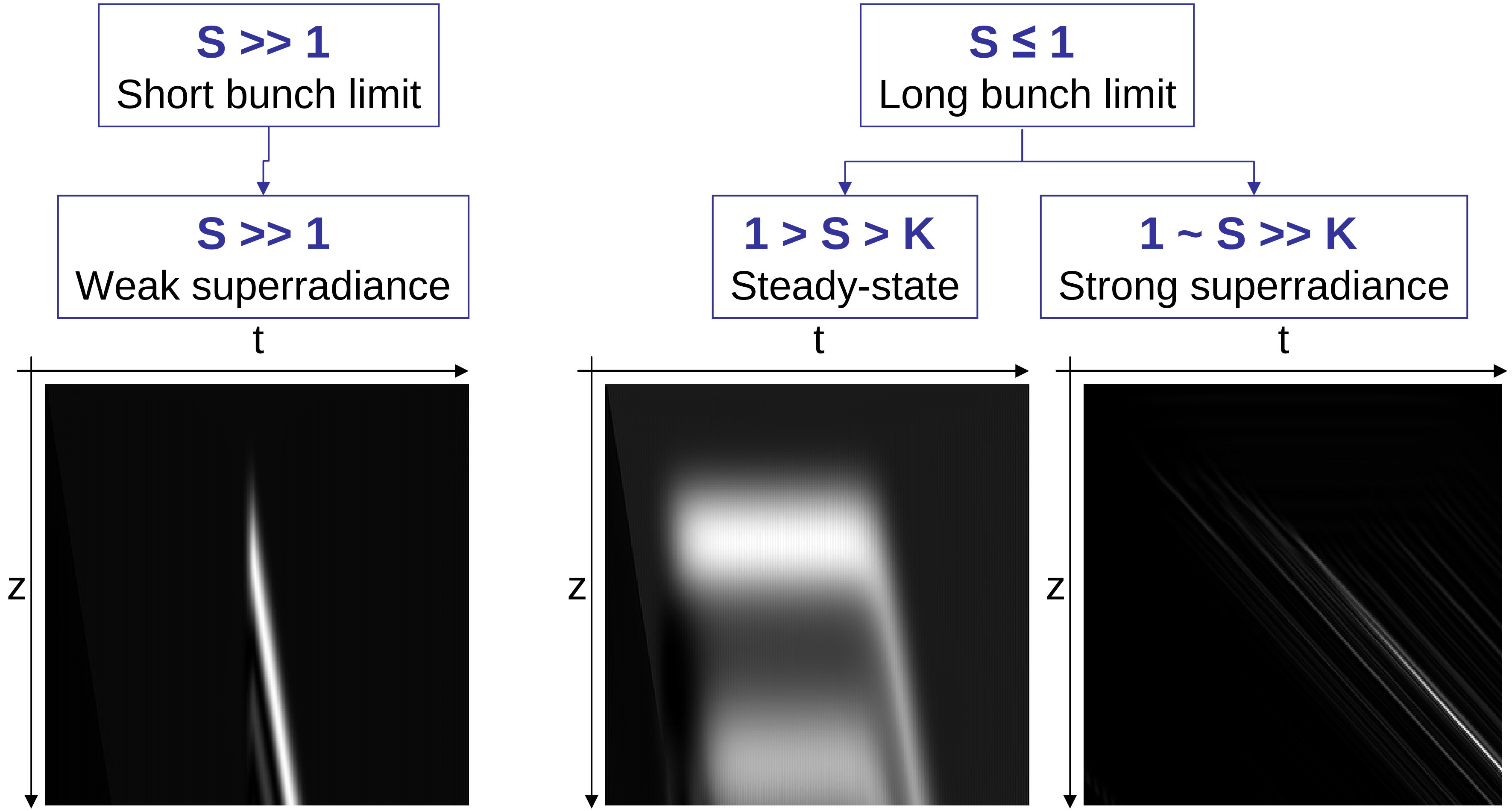
B. Bonifacio et al., PRA 40 (1989)



Analysis of the spatiotemporal regimes

« Initial » regimes

B. Bonifacio et al., PRA 40 (1989)



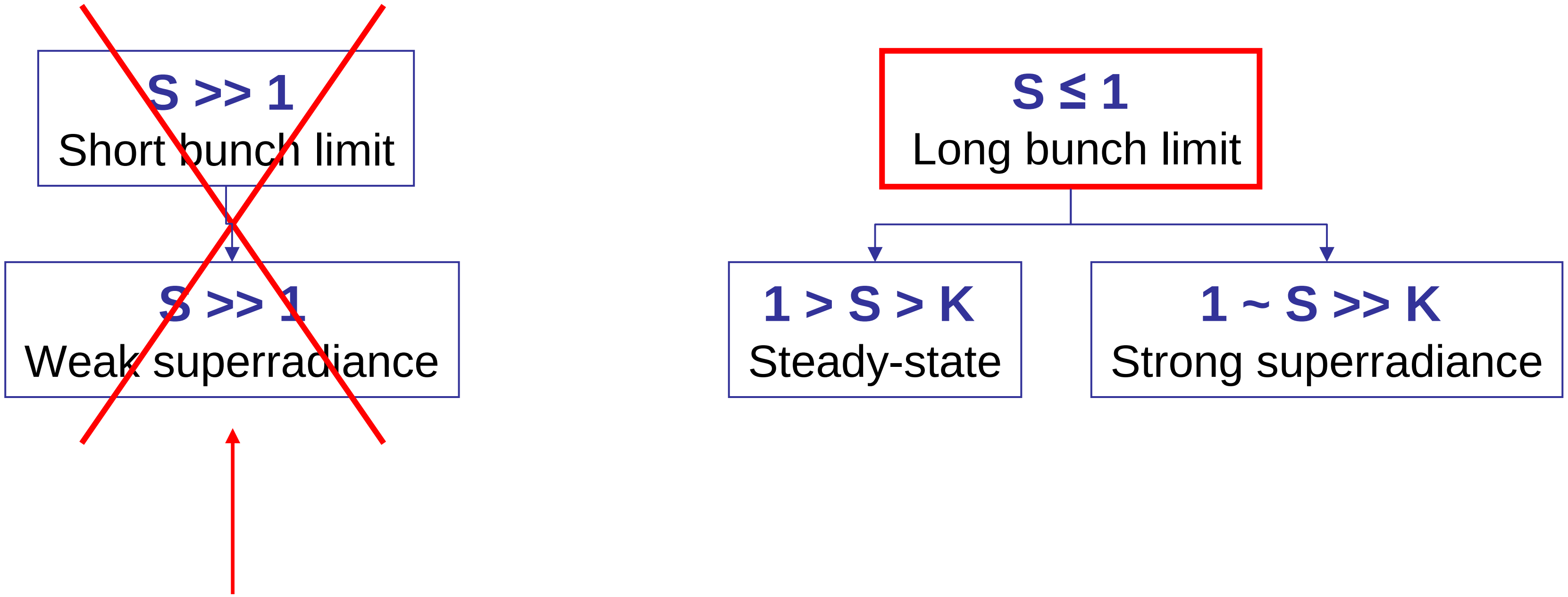
S_e=10

S_e=0.25, K=0.025

S_e=1, K=0.01

Analysis of the spatiotemporal regimes

« Initial » regimes



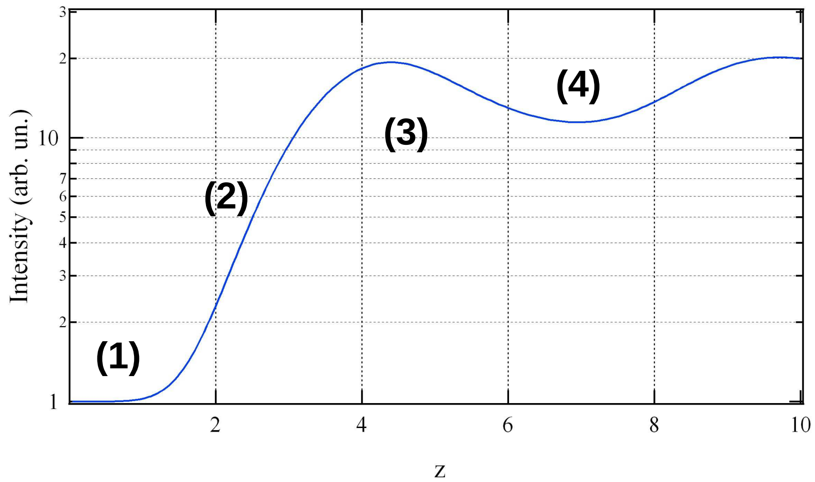
Today designs for S ≤ 1

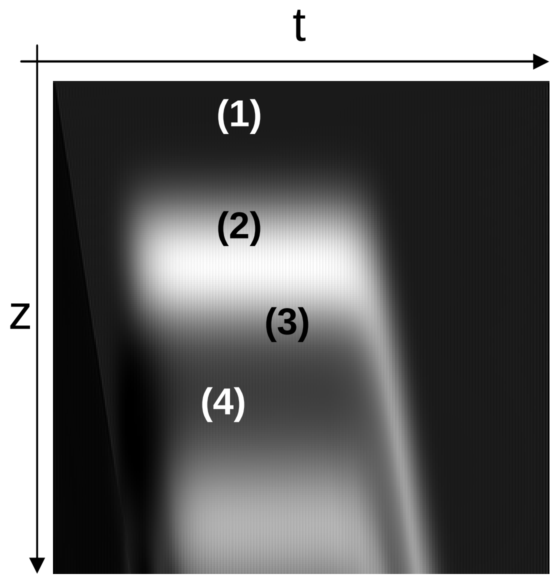
LCLS: S~0.01
EXFEL: S~0.02
FERMI: S~0.1
SPARC: S~0.07

Analysis of the spatiotemporal regimes

The steady-state FEL

- Condition for occurrence:
  - S ≤1 and 1>S>K (small slippage)
- Properties:
  - (1) Lethargy
  - (2) Exponential growth
  - (3) Saturation
  - (4) Power oscillations





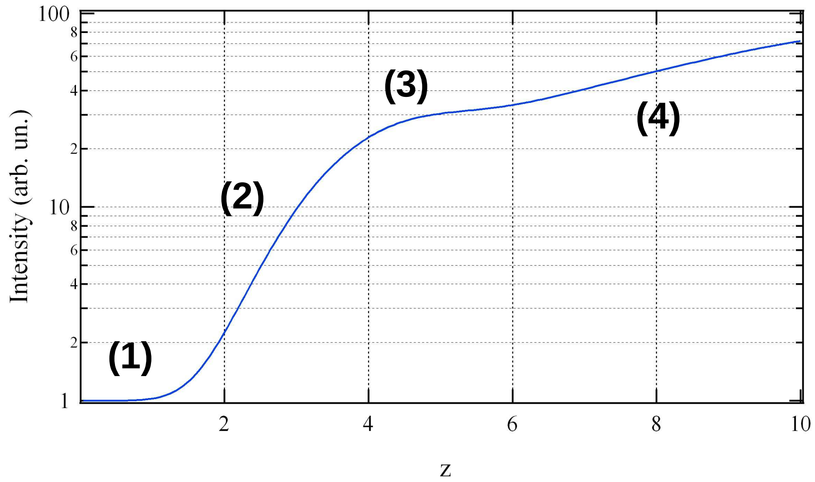
Analysis of the spatiotemporal regimes

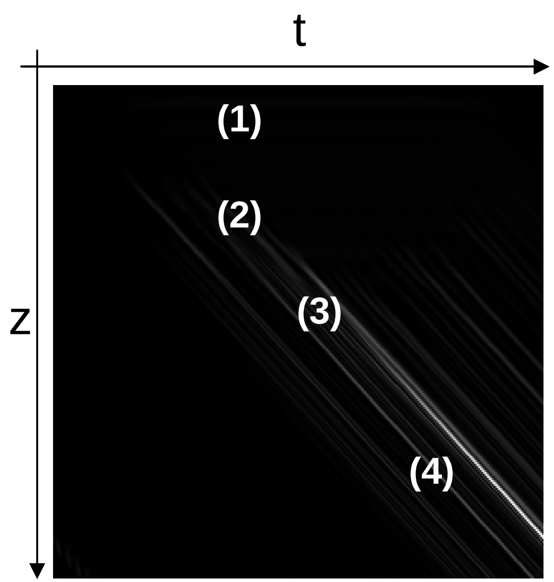
The strong superradiance

R. Bonifacio et al., PRA 40 (1989).

- Condition for occurrence:
  - 1 ~ S >> K

    (strong slippage)
- Properties:
  - (1) Lethargy
  - (2) Exponential growth
  - (3) No saturation
  - (4) …





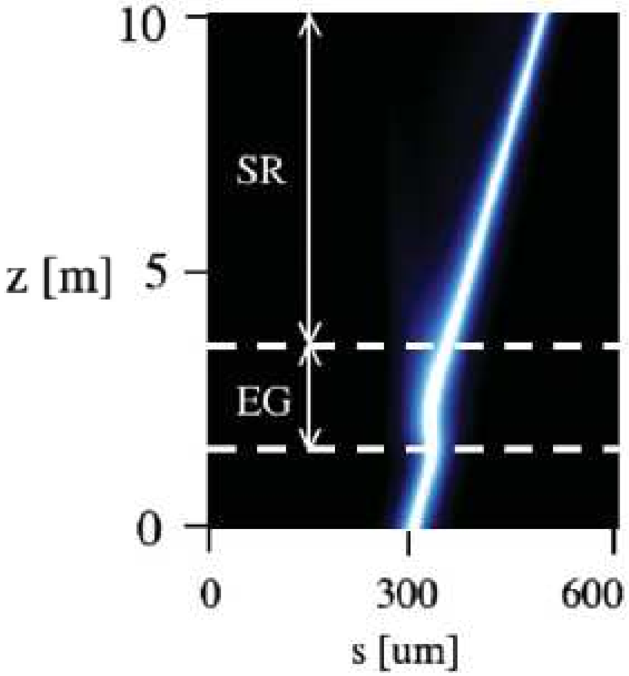
$$P \propto z^2$$
$$\sigma_z \propto z^{-1/2}$$

Analysis of the spatiotemporal regimes

The strong superradiance

T. Watanabe, PRL 98 (2007).

- Demonstration @ NSLS in 2007:

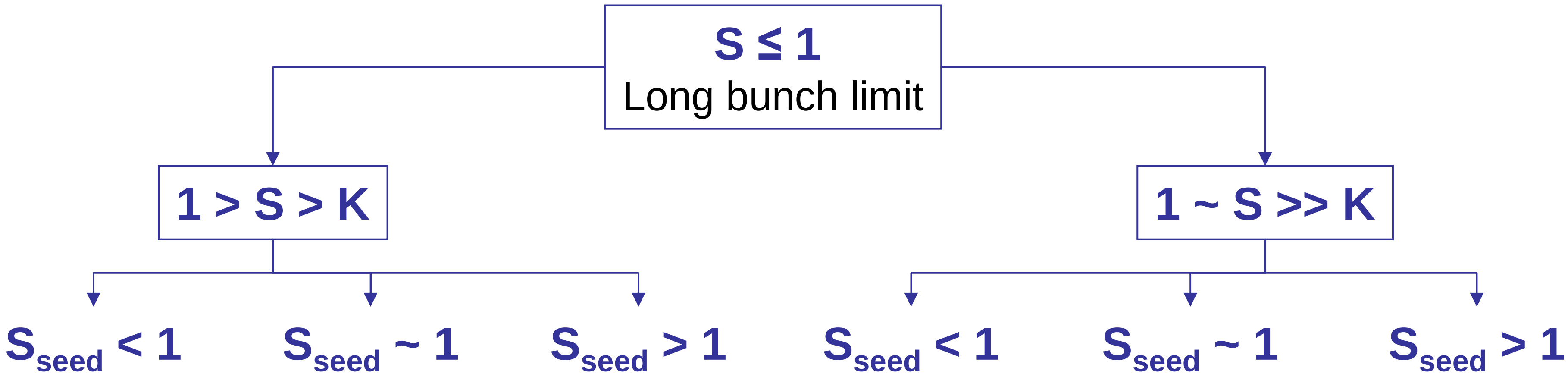


Analysis of the spatiotemporal regimes

The new regime

Analysis of the spatiotemporal regimes

The new regime



Analysis of the spatiotemporal regimes

The new regime

$S \leq 1$
Long bunch limit

- **$1 > S > K$**
  - **$S_{seed} < 1$** Steady state
  - **$S_{seed} \sim 1$** Pulse splitting
  - **$S_{seed} > 1$** Strong SR
- **$1 \sim S >> K$**
  - **$S_{seed} < 1$** Strong SR
  - **$S_{seed} \sim 1$** Strong SR
  - **$S_{seed} > 1$** Strong SR

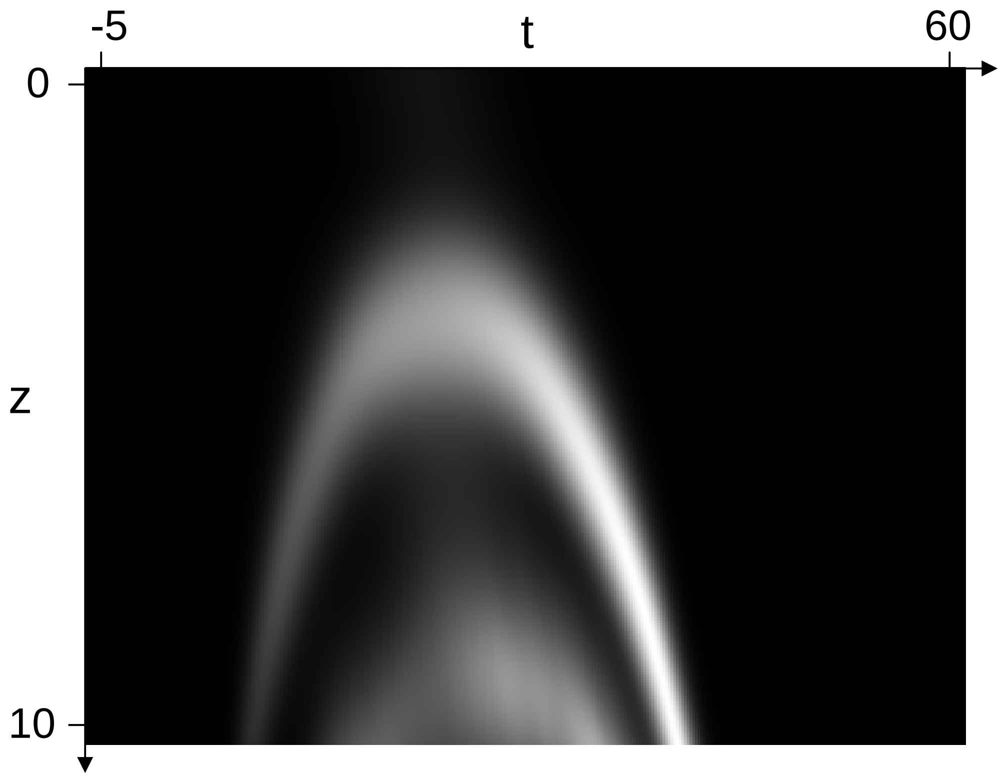
S_{seed}=0.25 | **S_{seed}=2** | **S_{seed}=10** | **S_{seed}=0.025** | **S_{seed}=2** | **S_{seed}=10**

S_e=0.25, K=0.025 | **S_e=1, K=0.01**

Analysis of the spatiotemporal regimes

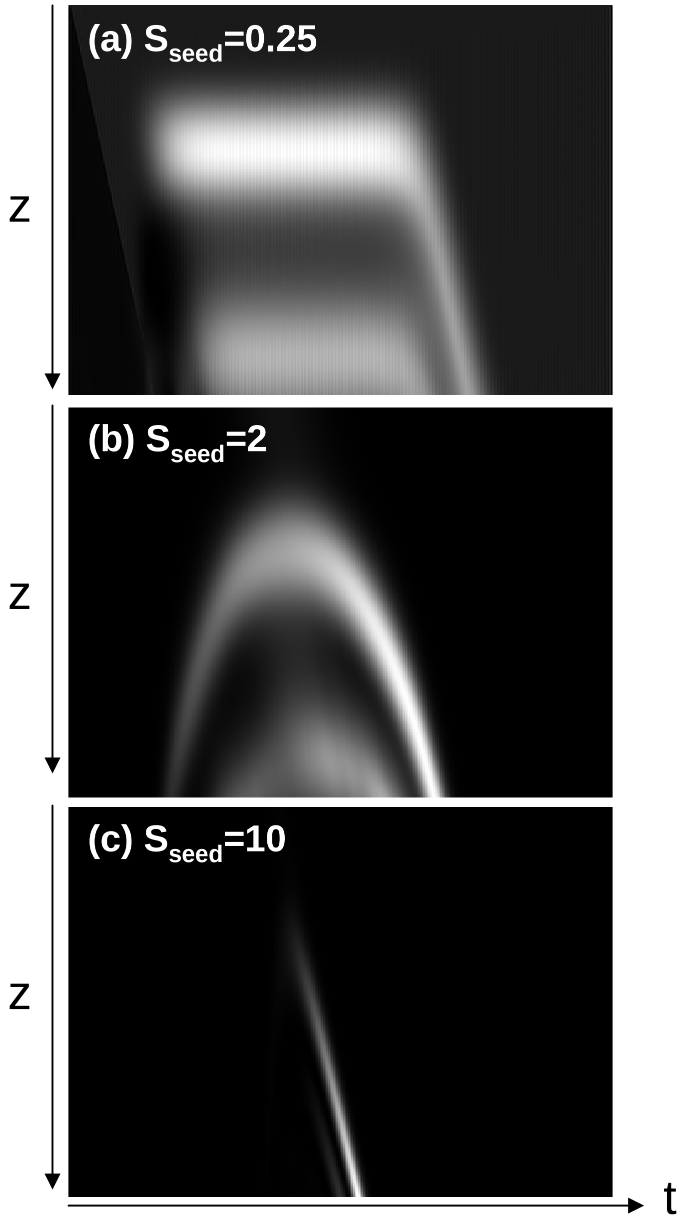
The pulse splitting

M. Labat et al., PRL 103 (2009)

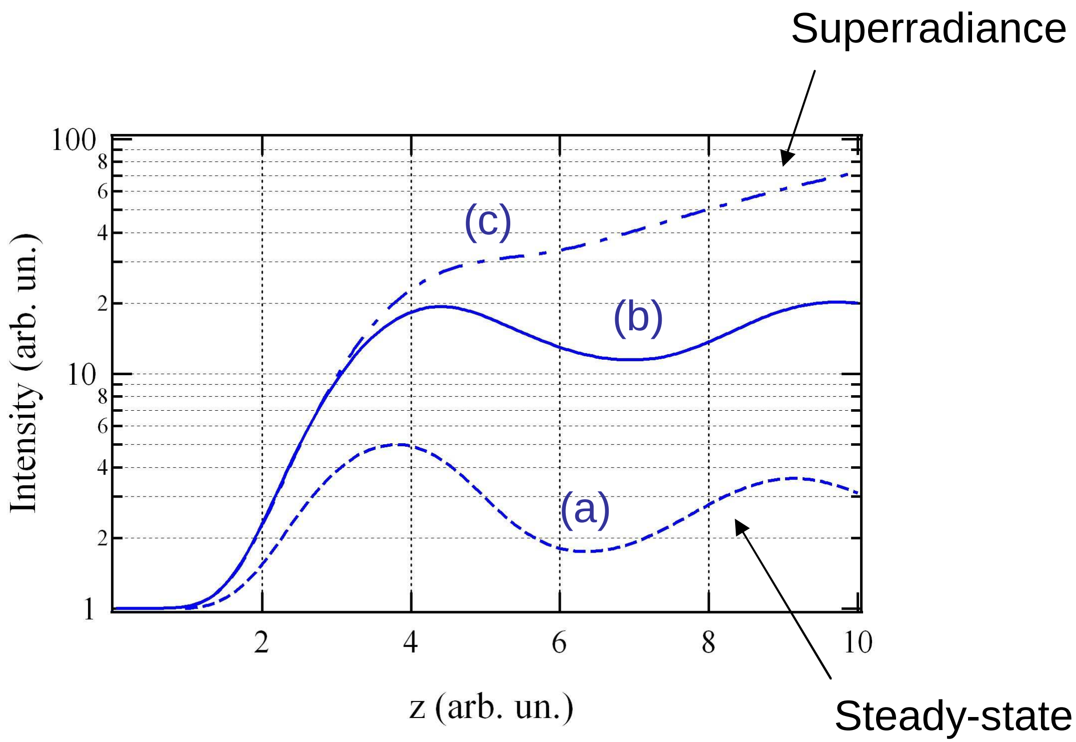


S_e=0.25, K=0.025, S_{seed}=2

The pulse splitting regime



Output power

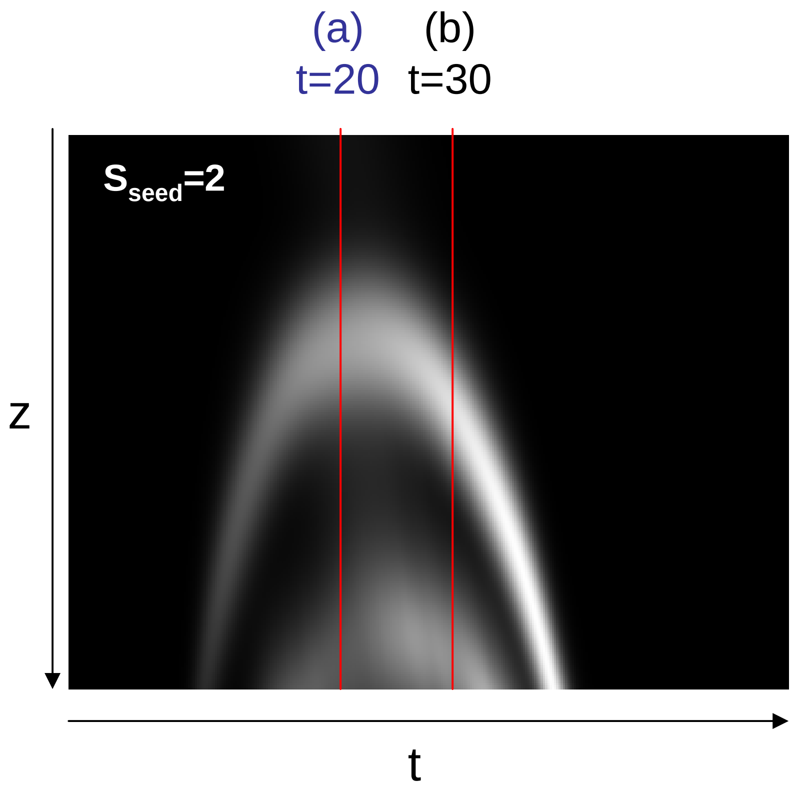


The pulse splitting regime

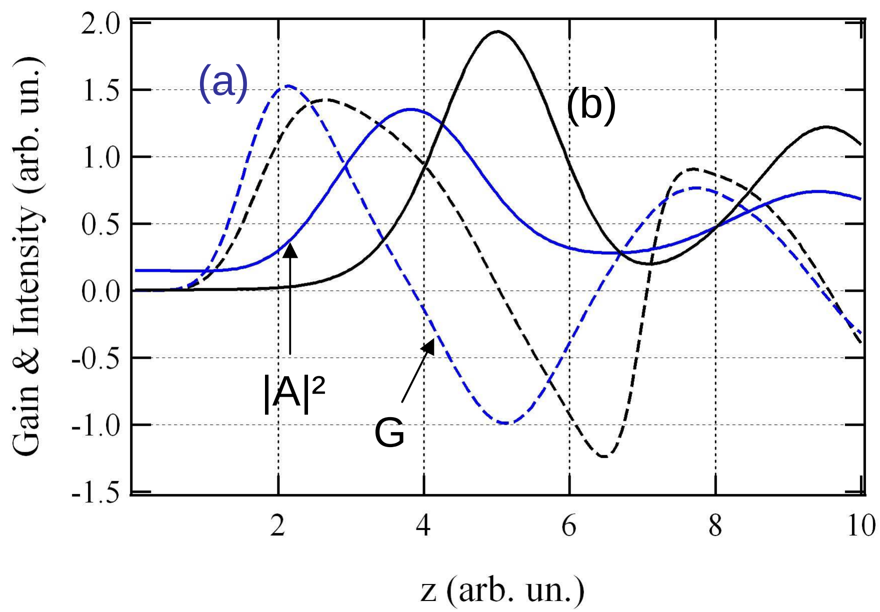
Gain

The pulse splitting regime

Gain

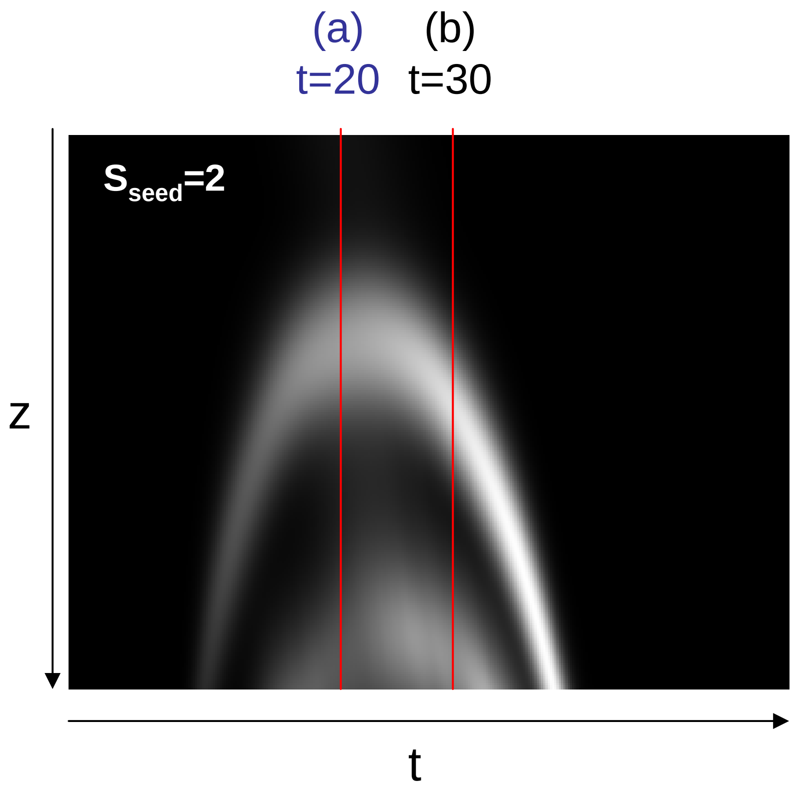


$$G(z,t) = Re[\frac{\chi(t)b(z,t)}{A(z,t)}]$$

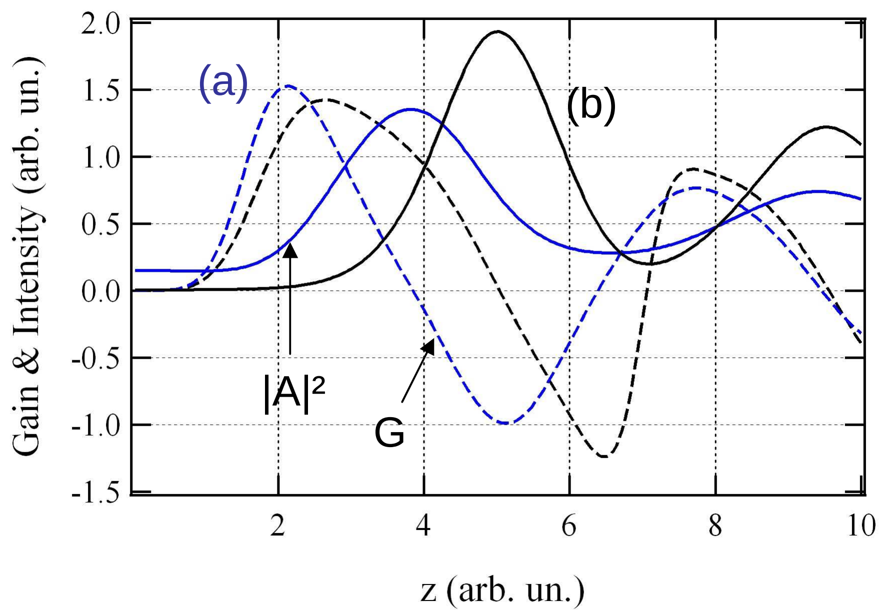


The pulse splitting regime

Gain



$$G(z,t) = Re\left[\frac{\chi(t)b(z,t)}{A(z,t)}\right]$$



Local gain → **Local saturation** → Progressive saturation along the pulse

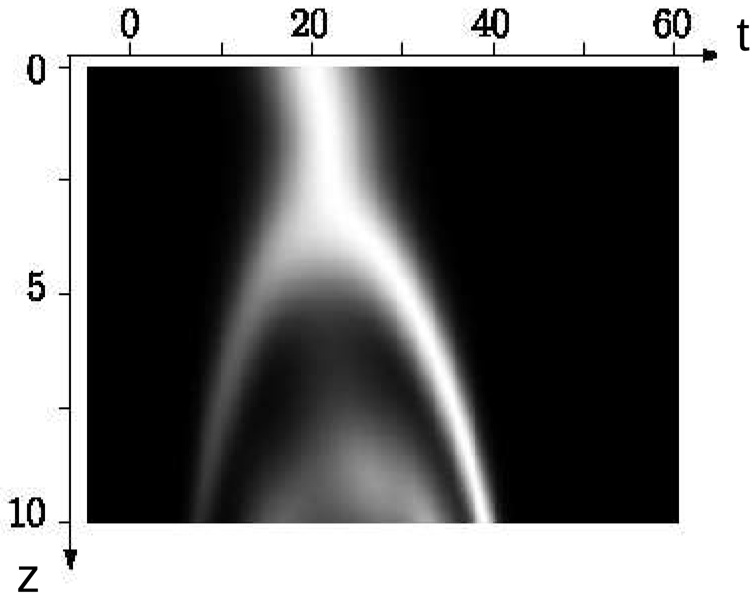
→ **Pulse splitting**

The pulse splitting regime

Approximative splitting equation

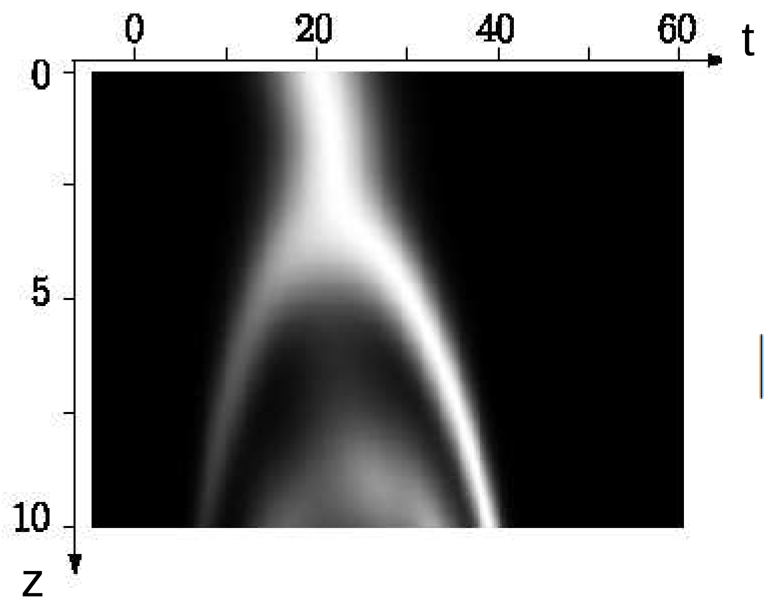
The pulse splitting regime

Approximative splitting equation



The pulse splitting regime

Approximative splitting equation



- For $S_e<1$ and $S_{seed}\sim 1$:

$$\left(\frac{\partial}{\partial z}+\frac{\partial}{\partial t}\right)A(z,t)\approx\frac{\partial}{\partial z}A(z,t)$$

- Solution of FEL equations:

$$|A|^2(z,t)\approx\frac{1}{9}exp[\sqrt{3}z]|A|^2(z=0,t)$$

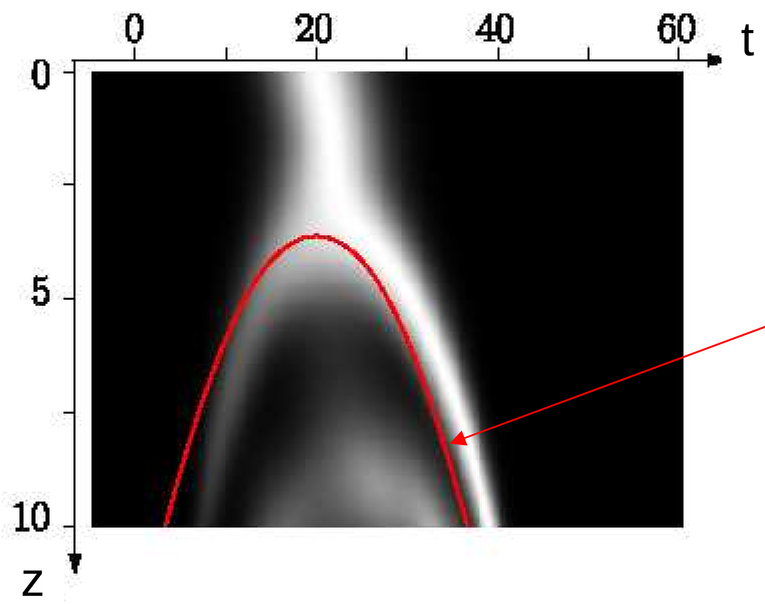
- At saturation:

$$|A|^2(z_{sat},t)\cong O(1)\cong 1.4$$

B. Bonifacio et al., NIMA239 (1985)

The pulse splitting regime

Approximative splitting equation



$$z_{sat}(t) = \frac{1}{\sqrt{3}} ln[\frac{9 \times 1.4}{|A|^2(z=0,t)}]$$

CONFIRMS

- Local gain → **Local saturation** → Progressive saturation along the pulse
- ➡ **Pulse splitting**

The pulse splitting regime

Next step

Can we observe a pulse splitting
on an existing seeded FEL ??

Pulse splitting in seeded FELs

Conclusion

- Simulation of VUV and XUV seeded FELS (ARC-EN-CIEL):
  → Observation of a pulse splitting
- Studies under PERSEO:
  → Rough understanding

- Integration of FEL equations:
  → Observation of a pulse splitted regime
- Analysis of dimensionless parameters:
  → Definition of the regime conditions of occurrence
  → Better understanding of the phenomenon

→ **Let's make experiment….**