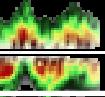




Towards table-top free-electron lasers (FELs) using laser- accelerated electron beams

Matthias Fuchs



ute

Name(s)

Task

R. Weingartner, A. Maier, S. Becker, J. Osterhoff, A. Popp, Zs. Major, S. Karsch, D. Habs, F. Krausz, **F.Grüner**

FEL team
electron acceleration
laser development



S. Reiche

initial FEL simulation



W. Decking, T. Limberg, H. Schlarb, M. Dohlus, K. Flöttmann, C. Gert, K. Tiedtke, B. Schmidt

diagnostic, space-charge
wakefields



A. Meseck, J. Bahrdt, A. Gaupp

full FEL simulation
cryogenic undulator
diagnostics



T. P. Rowlands-Reese, S.M. Hooker

electron acceleration



C. Schroeder, E. Esarey, B. Fawley, W. Leemans

FEL design studies
staged acceleration



Free-Electron Laser (FEL) theory

Laser-Wakefield Acceleration of Electrons theory experimental results

Table-top FEL theory

laser-driven Ultrashort Soft-X-Ray Undulator Source experimental results



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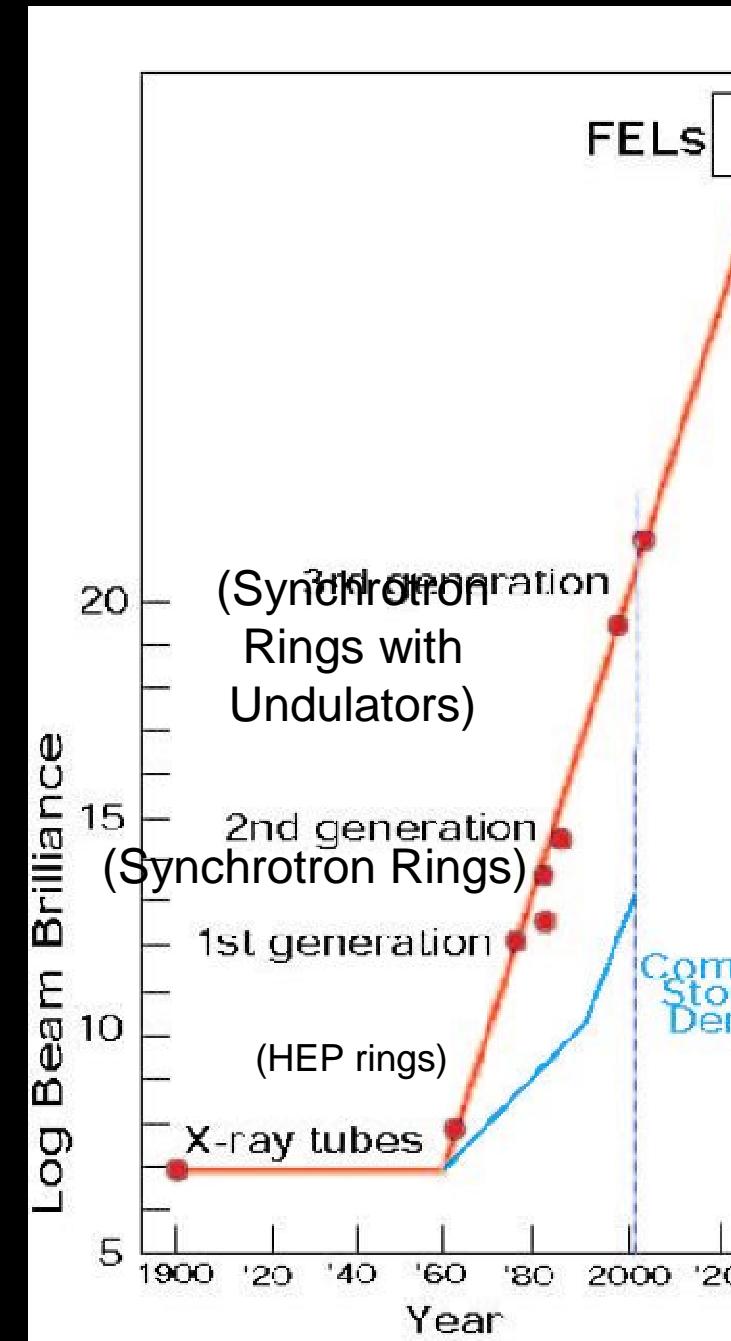


length on the order of Angstrøm
investigation of atomic-sized objects

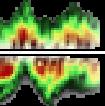
ns pulses

time scale of chemical reactions
time scale of electron motion in

high brilliance



picture
Sole
Fran

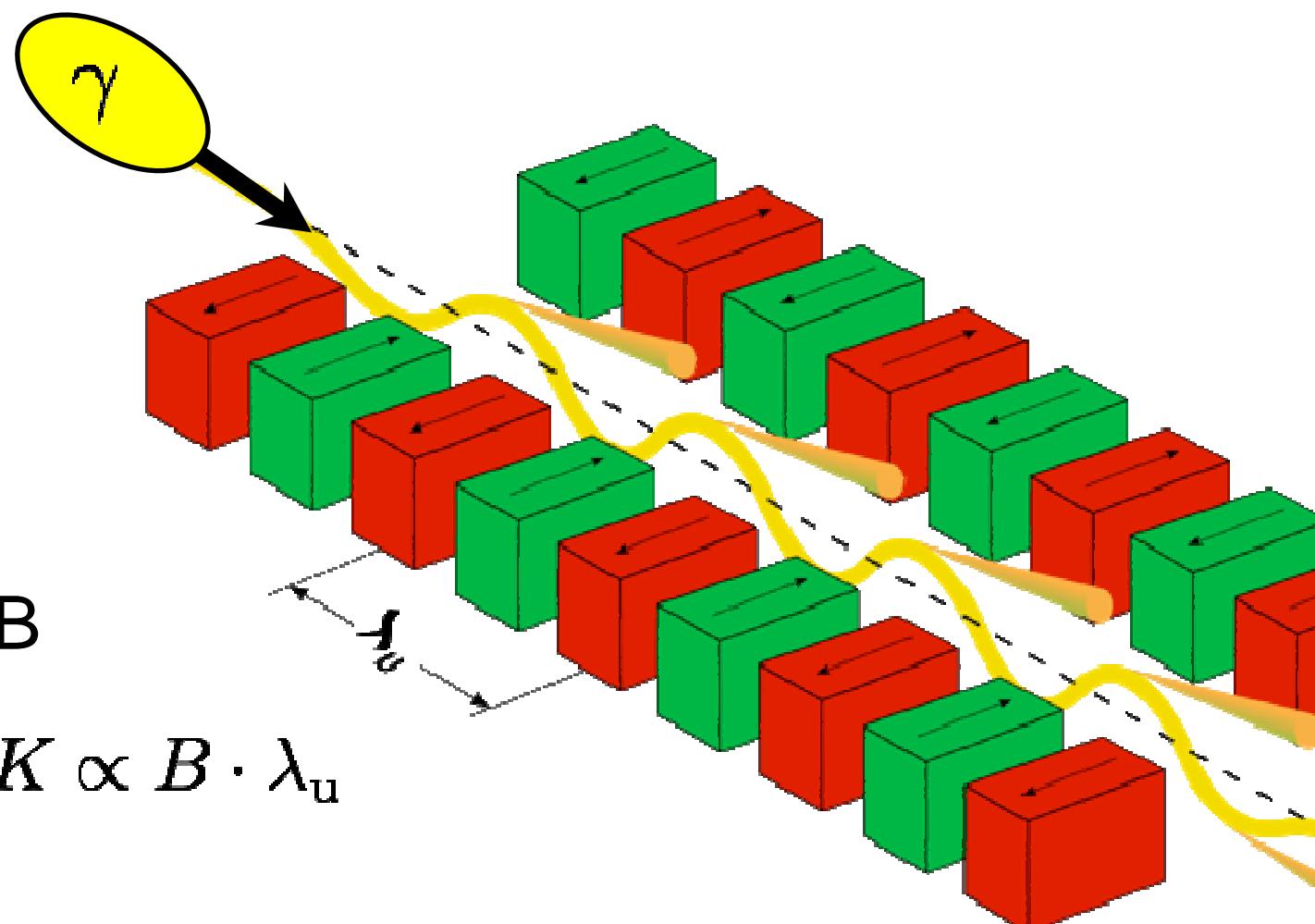


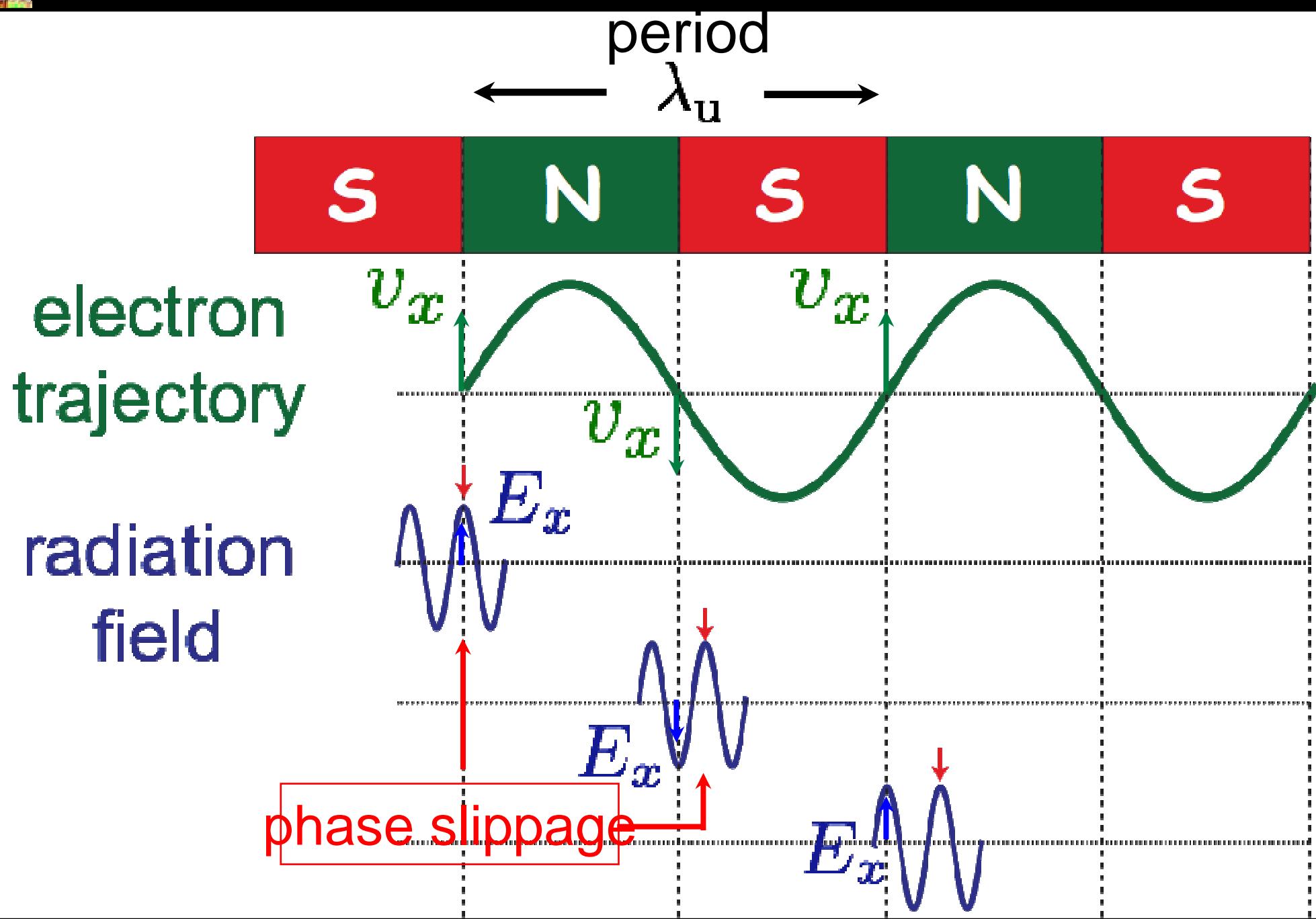
ultrarelativistic electron beam

lator period: λ_u
netic field [on axis]: B
ction parameter:
ron energy:

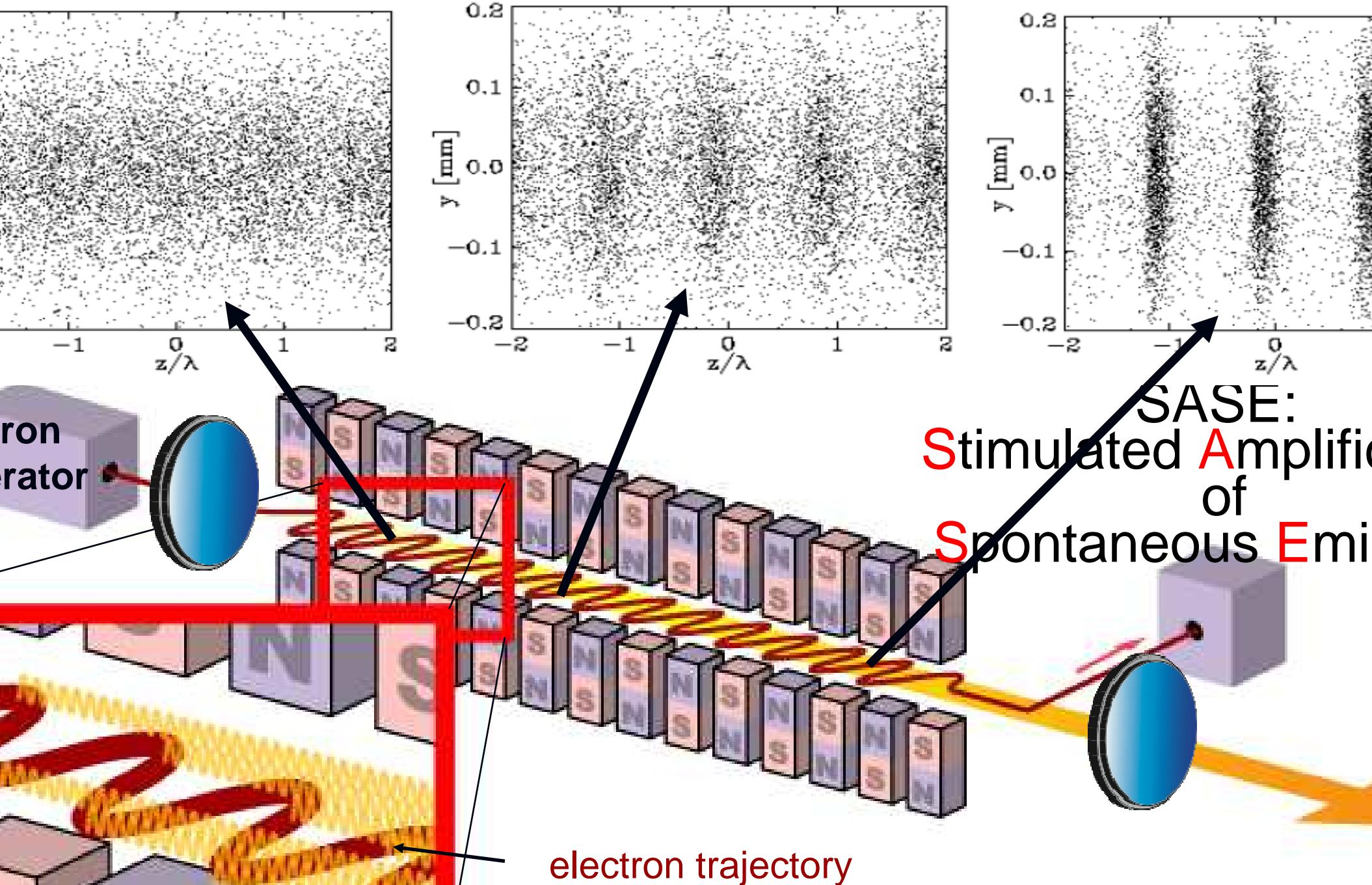
$$K \propto B \cdot \lambda_u$$

γ



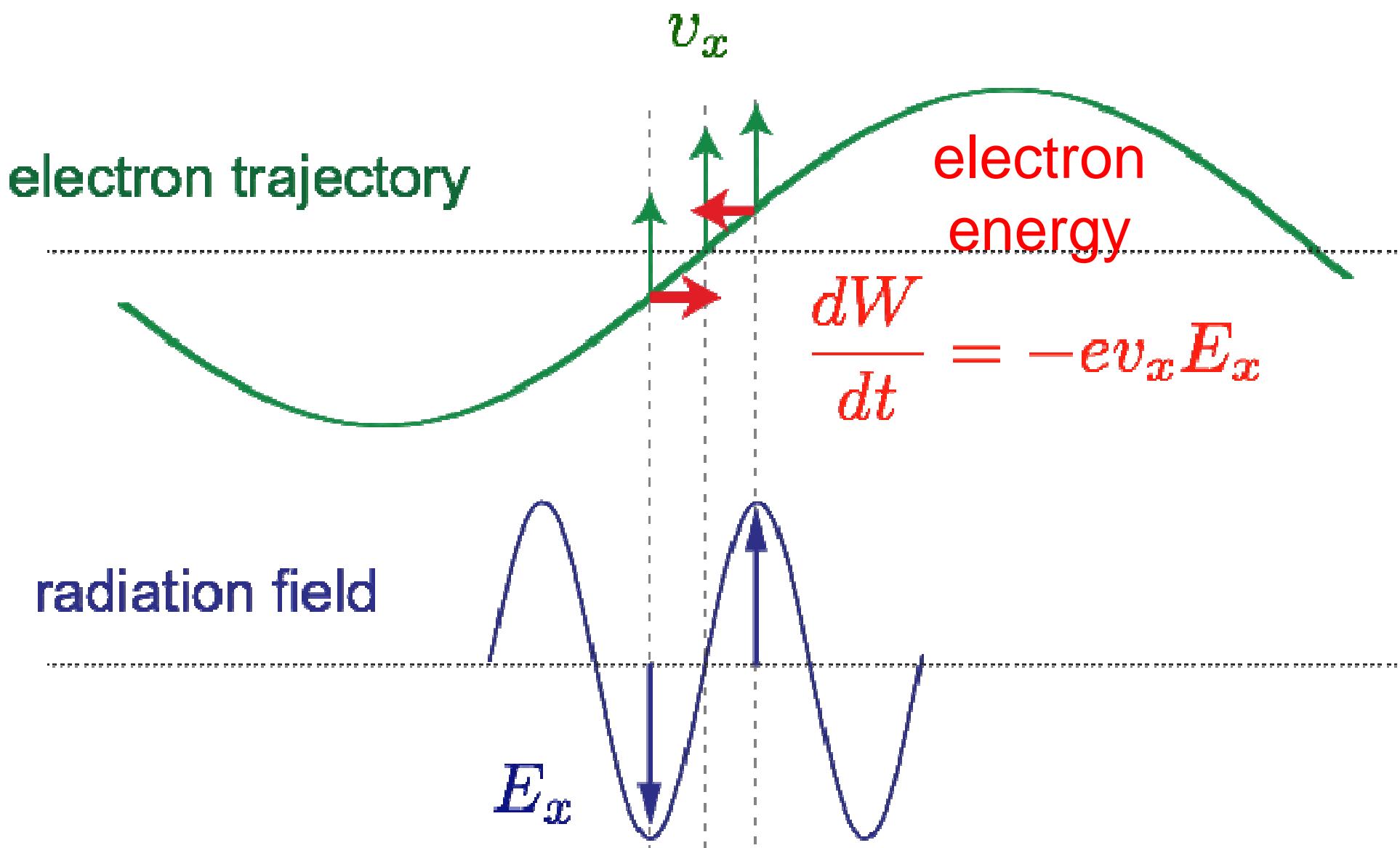


$$\lambda_{\text{res}} = \frac{\lambda_u}{2} \left(1 + \frac{K^2}{\omega} \right) \quad K \propto B_0 \lambda_u$$





8



QuickTime™ and a
Animation decompressor
are needed to see this picture.

courtesy: S. Reic

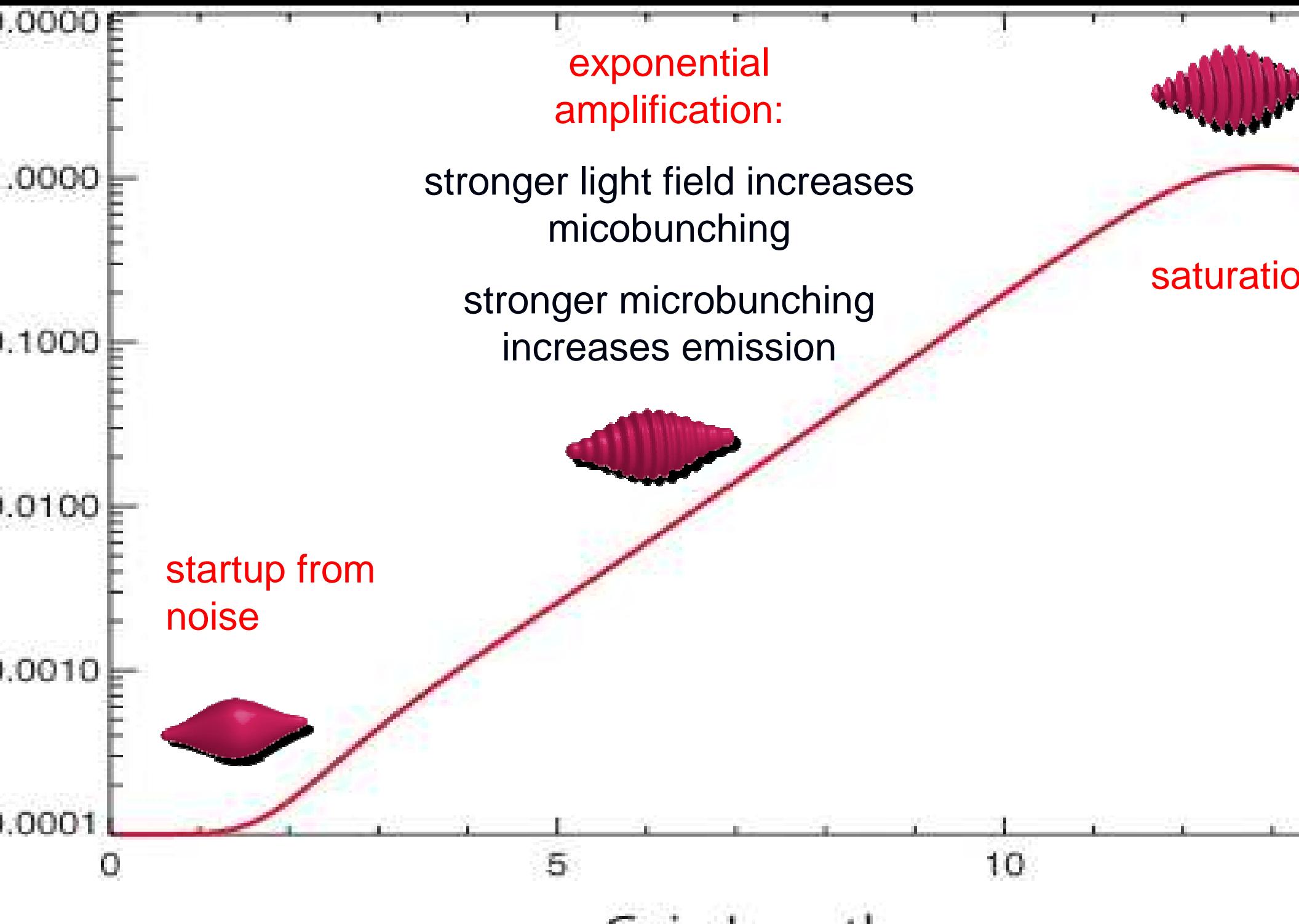
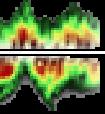
coherent
emission:
 $\propto N_e$

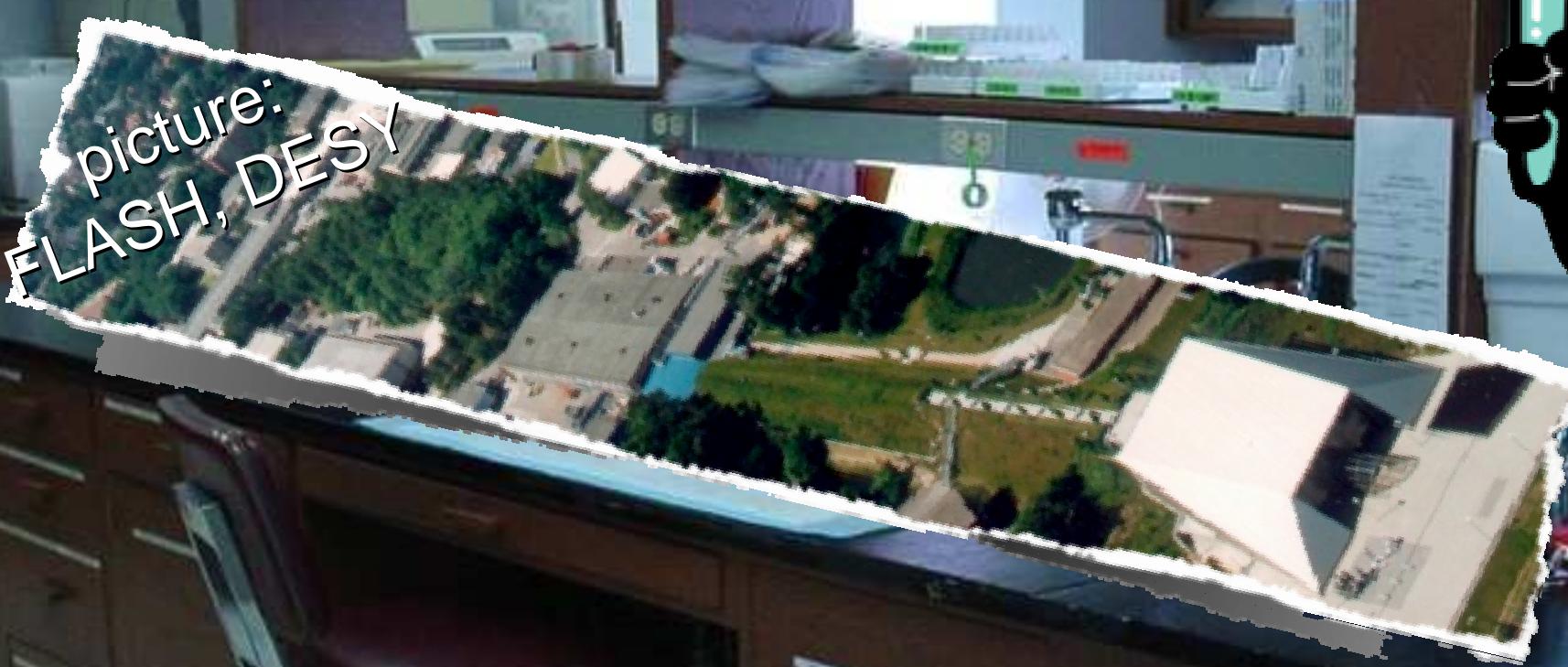
$$I \sim I_0 \left[N_e + N_e(N_e - 1) \exp\left(-\frac{(2\pi)^2}{\lambda^2} \sigma_s^2\right) \right]$$

cohe
emis
 $I \propto$

it' all about coherence !









Free-Electron Laser (FEL) theory

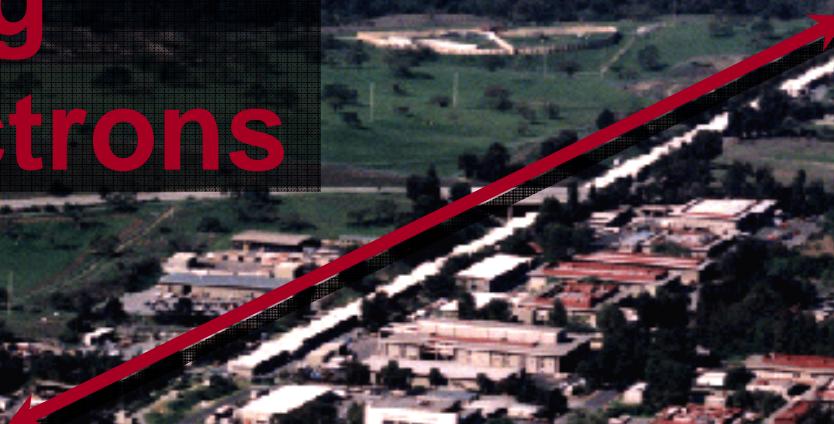
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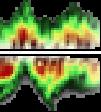
laser-driven Ultrashort Soft-X-Ray Undulator Source experimental results

LAC, California

2 km long
14.3 GeV electrons



Accelerating fields are 20 MV/m



-in-
tion

e"
Vehn,
OV
ys B,
(2002)



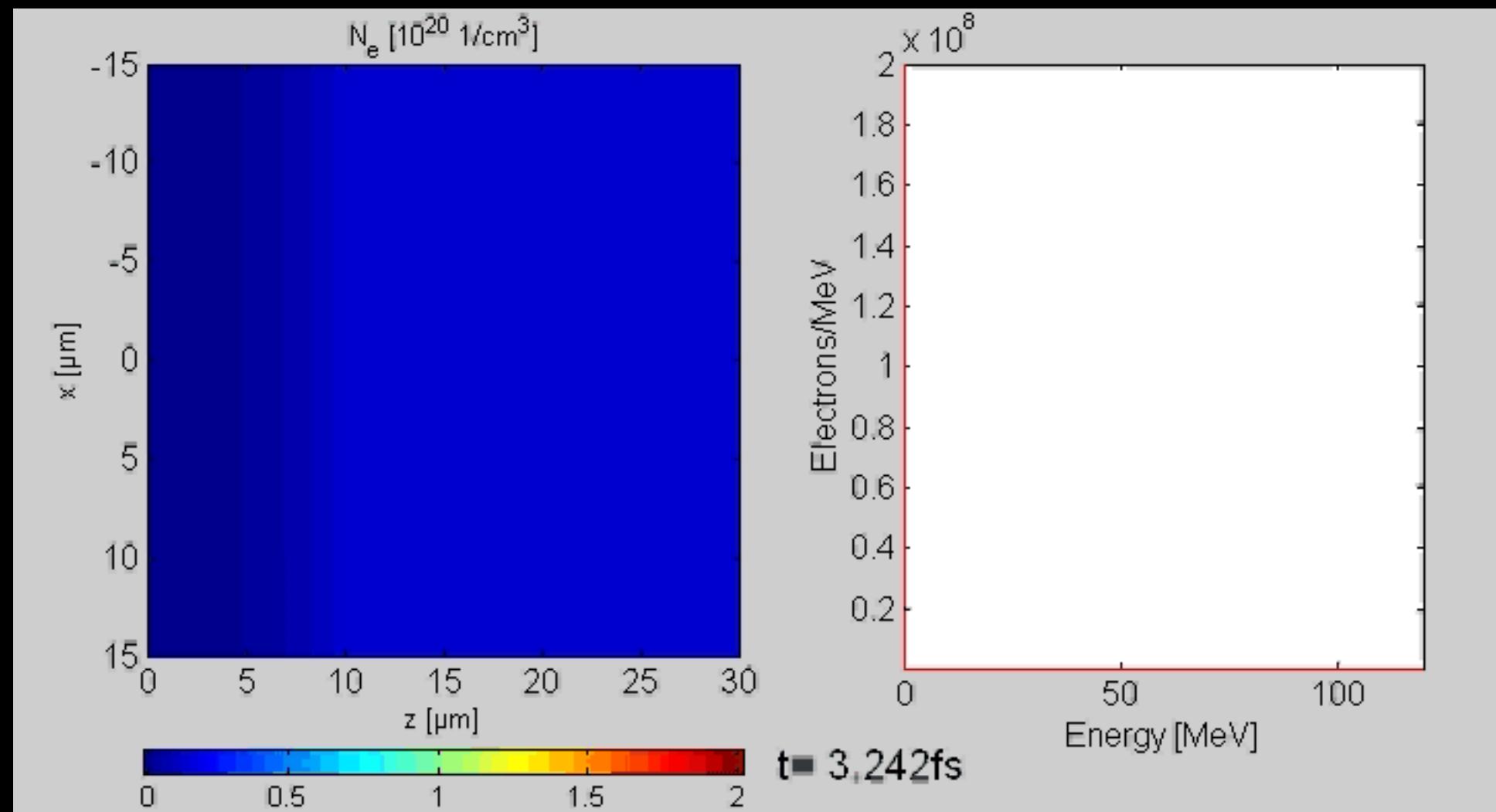
laser excites a plasma
wakefield

• for high enough laser energy density:
 $E = 10^{17} \text{ eV}$ ($T = 10^{17} \text{ eV}$)
the wave breaks & electrons are accelerated

0 60 65 70 75 80 85 90 95 100

0.010
0.001

0.001





PIC-Simulation by Michael Geissler, MPQ / Queen's University



Generating electric fields $E_{\max} [\text{V/cm}] \simeq 0.96 \sqrt{n_e [\text{cm}^{-3}]}$

$$n_e = 10^{18} \text{ cm}^{-3} \Rightarrow E_{\max} = 100 \text{ GV/m}$$

lasing length:

$$n_e^{-3/2}$$

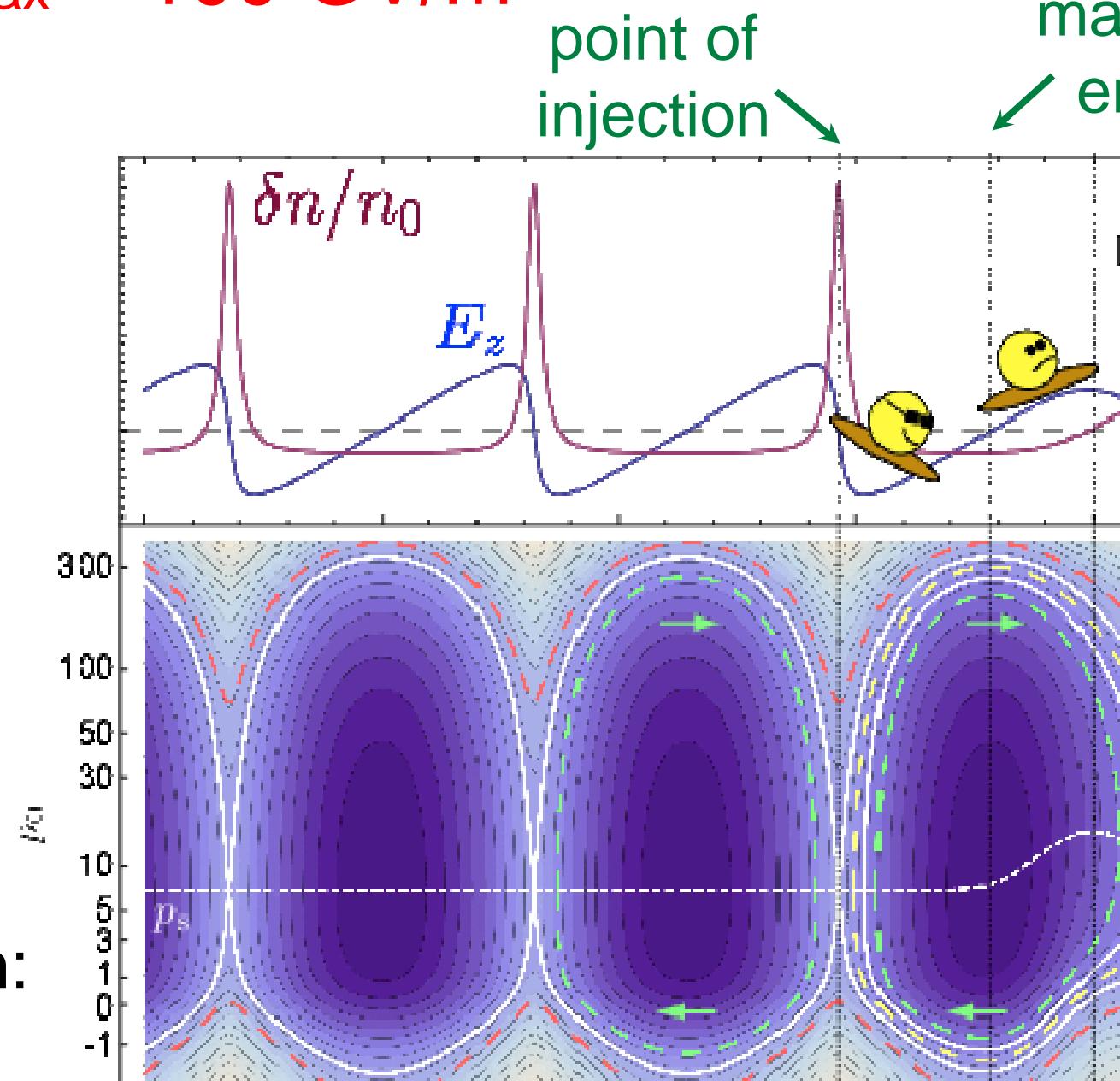
electron

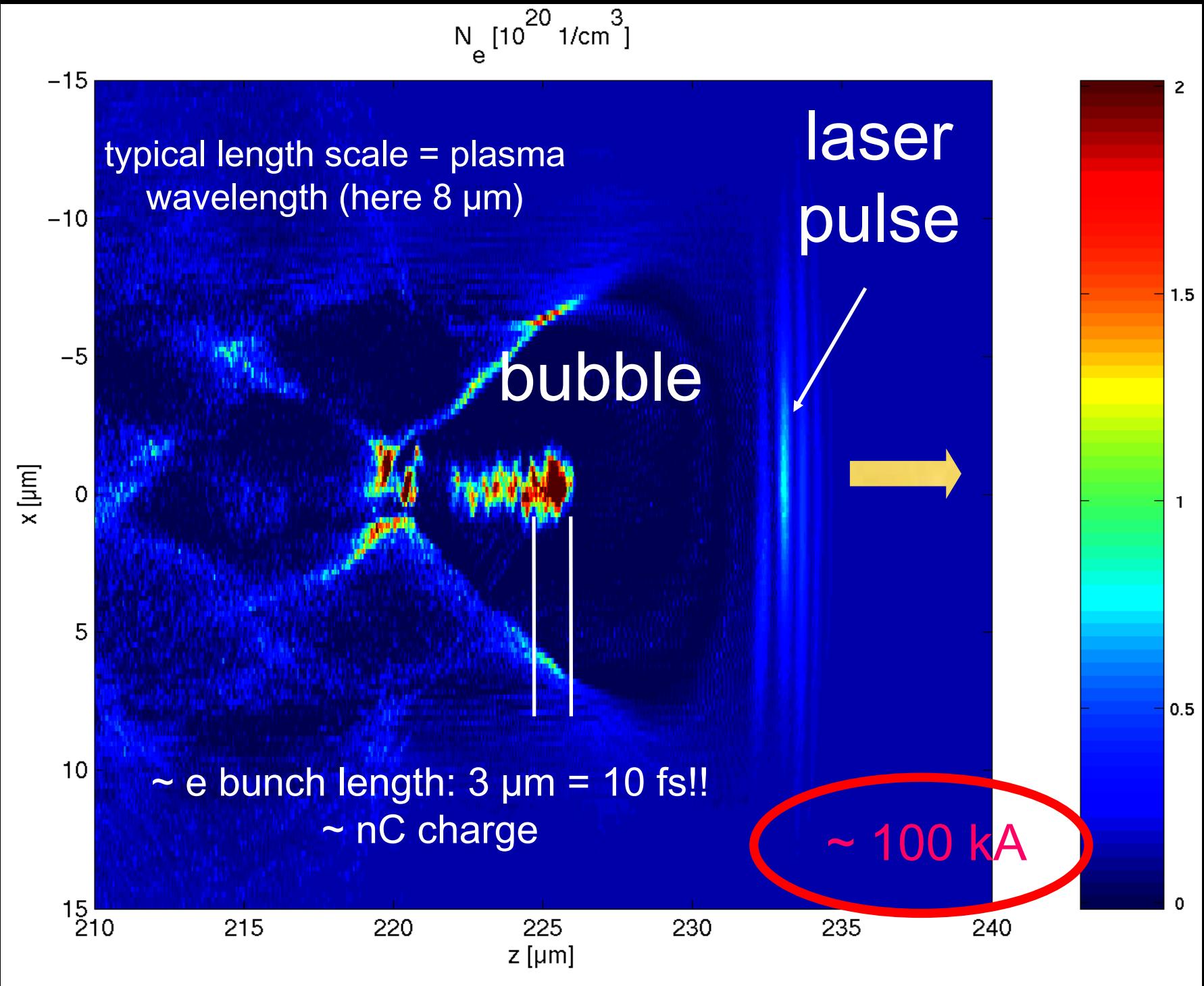
$$= eE_{\max}L_d \propto \frac{1}{n_e}$$

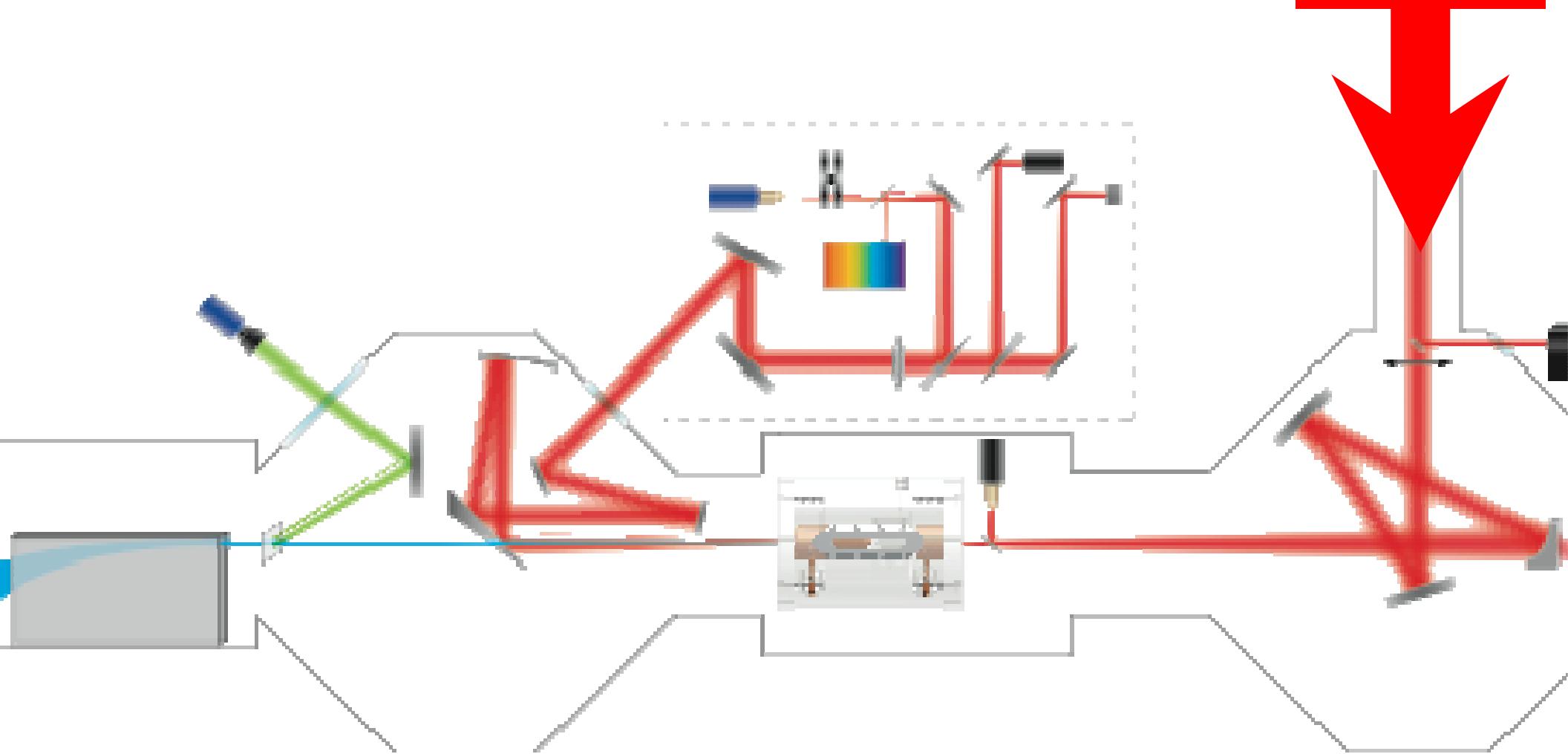
$\propto I_{\text{laser}}$

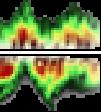
electron bunch

on
of plasma wavelength:
5 μm (50 fs)





 ATLAS1 J
35 fs



8 mm

0.6 mm

250 μm Electron
beam

Gas out

Sapphire block

15 mm

Gas in



Gas in

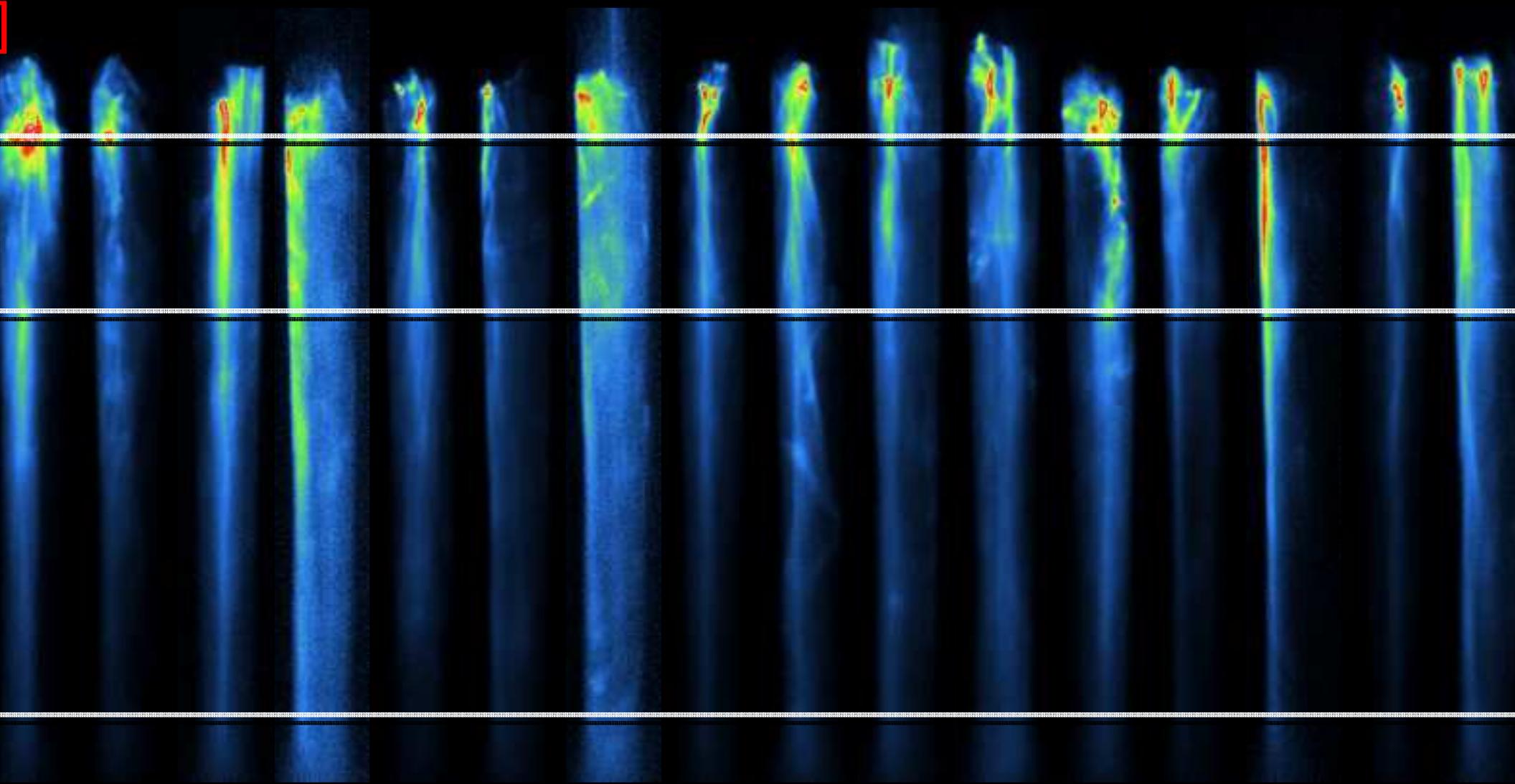
Gas out

ATLA

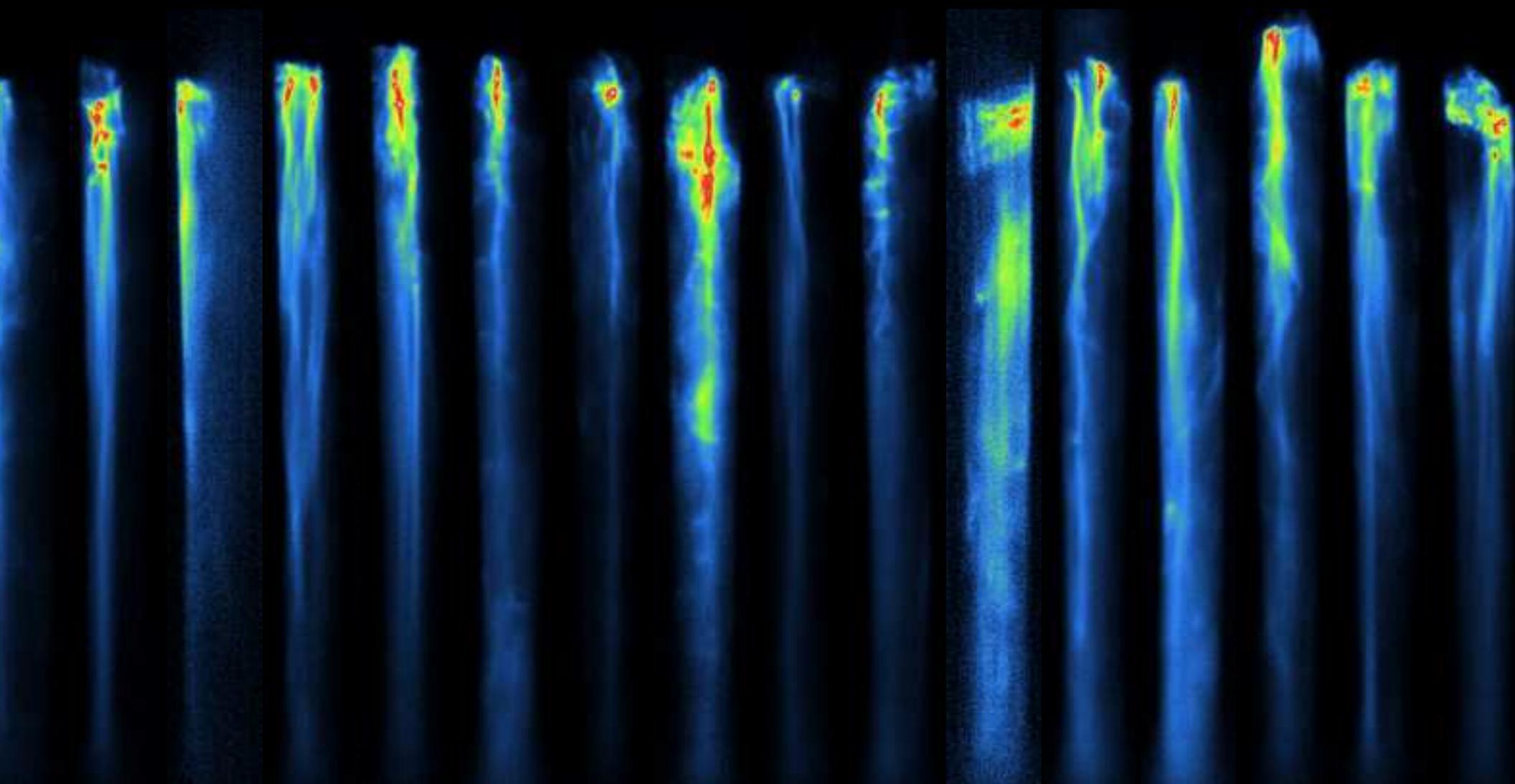
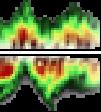
200



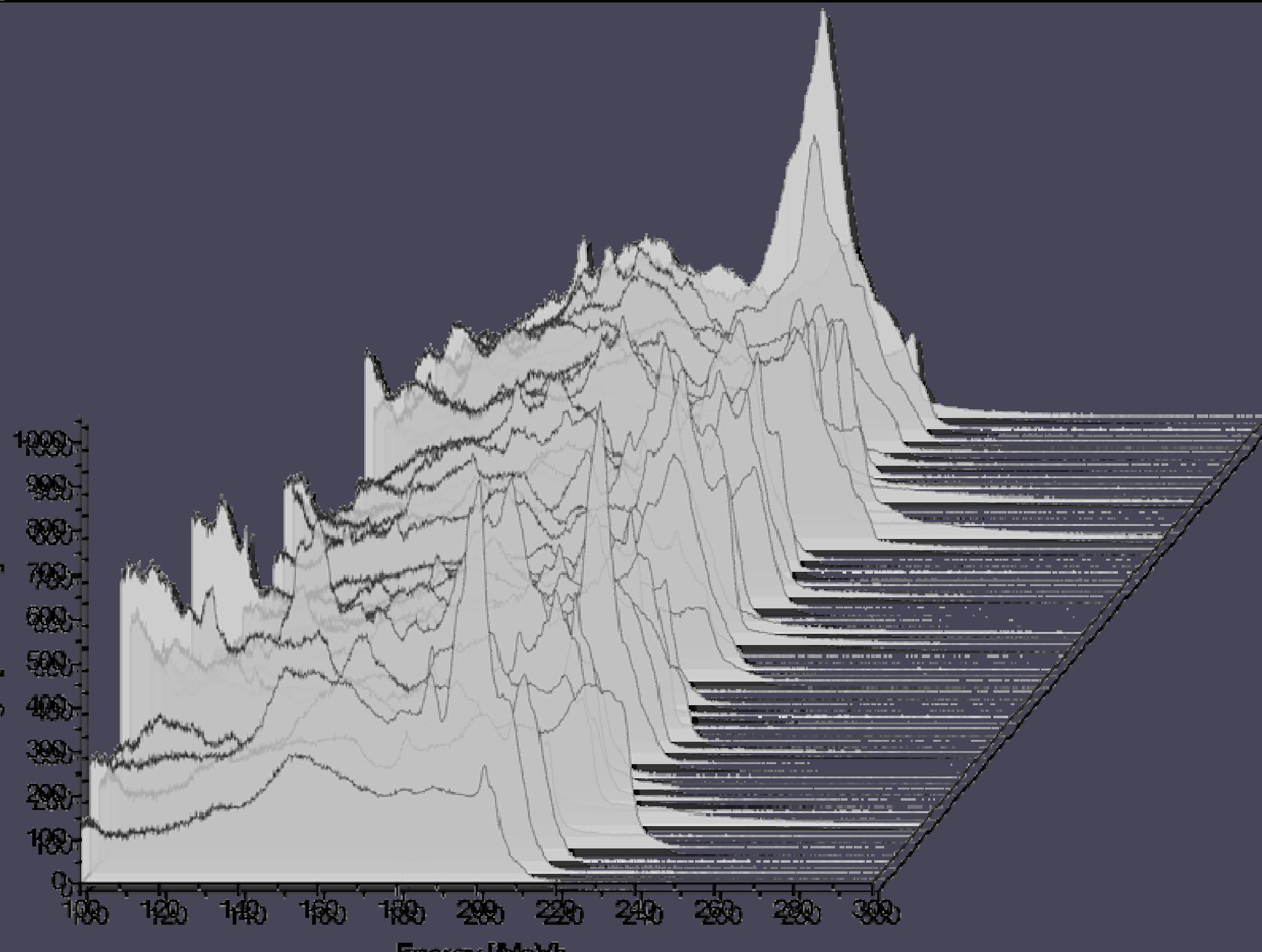
on
y
]



$$= 7.3 \cdot 10^{18} \text{ cm}^{-3}$$



J. Osterhoff, et al., *PRL* 101, 085002





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simplest estimate: **ideal** 1D FEL theory (no energy spread, emittance, diffraction, time-dependence)

e-folding length:

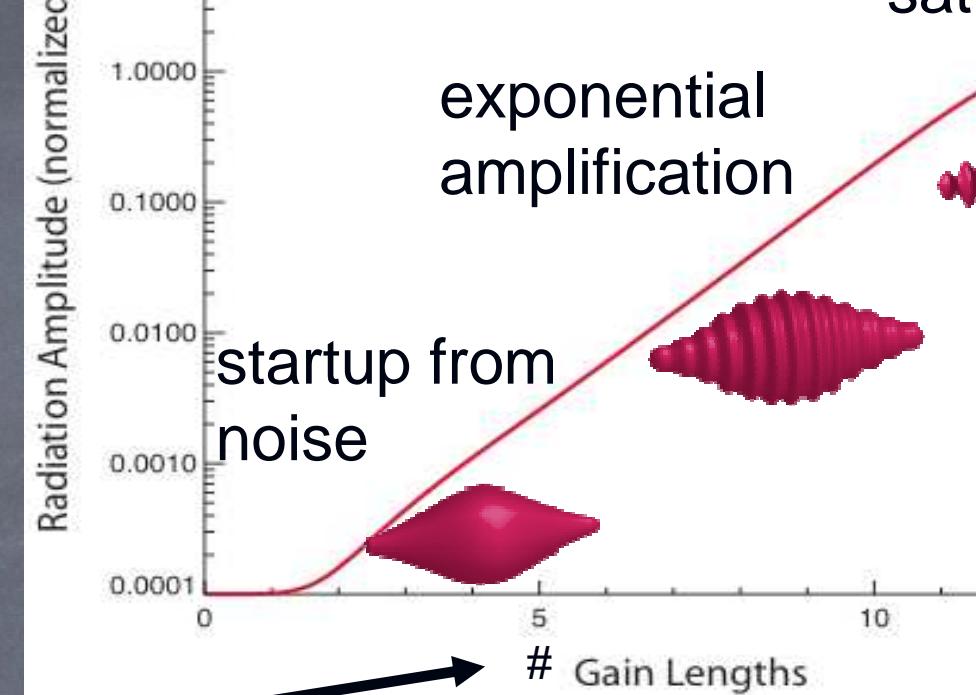
Pierce parameter:

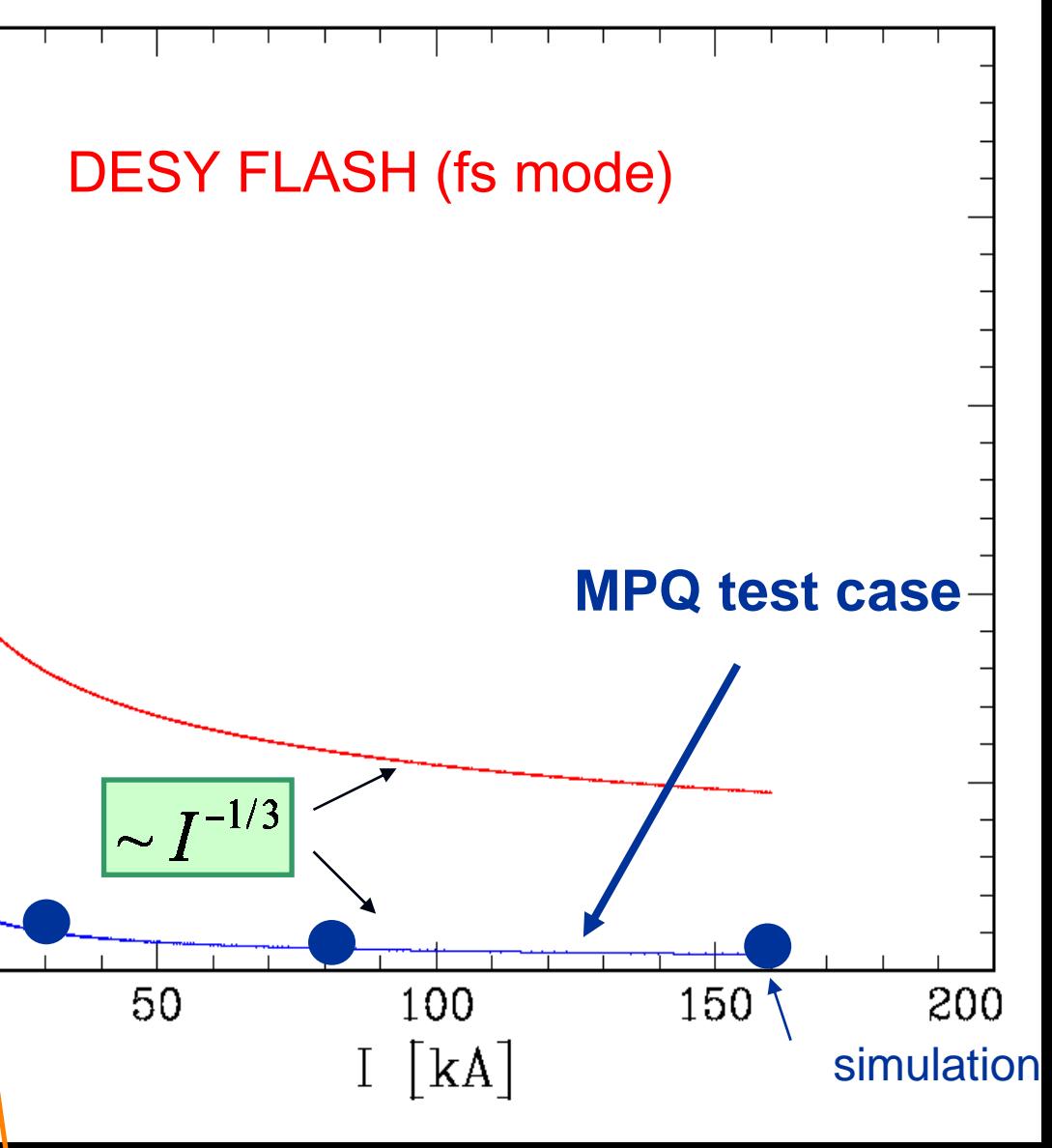
undulator length:

$$L_{\text{gain}} = \frac{\lambda_u}{4\pi\sqrt{3}\rho}$$

$$\rho \sim \frac{1}{\gamma} \left(\frac{I}{I_A \sigma_x^2} \right)^{1/3} \lambda_u^{4/3}$$

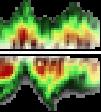
$$L_{\text{sat}} \approx (15 - 25) \cdot L_{\text{gain}}$$





Alfven
current
17kA)

FLASH	(fs)	F
radiation wavelength	30 nm	32
undulator period	27.3 mm	5
electron beam energy	461.5 MeV	150
beam size	170 μm	30
current	1.3 kA	50
Pierce parameter ρ	0.002	0
energy spread	0.04%	0
pulse length	55 fs	4
saturation length	19 m	0.

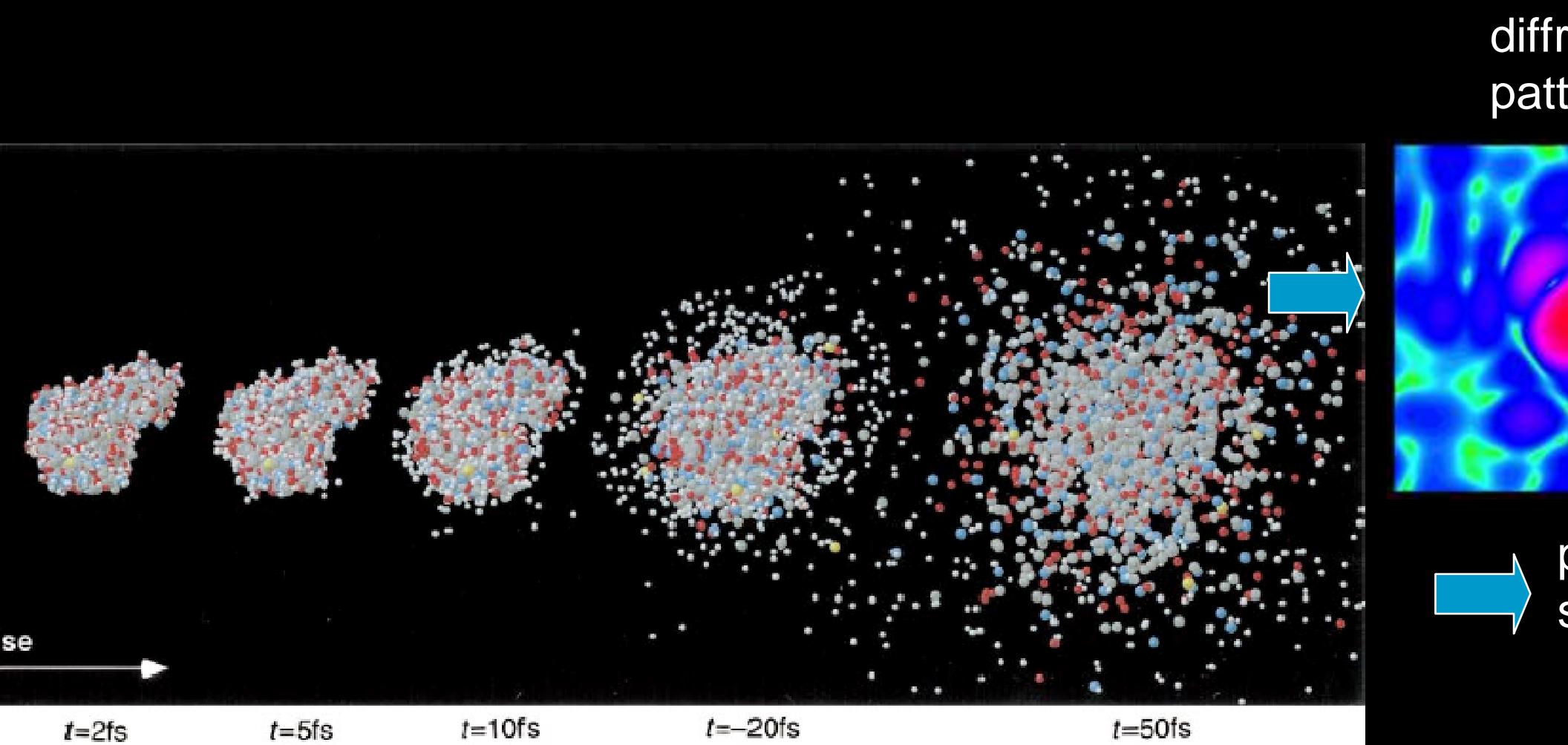


Single Molecule Imaging

Image of sub-10fs FEL pulses

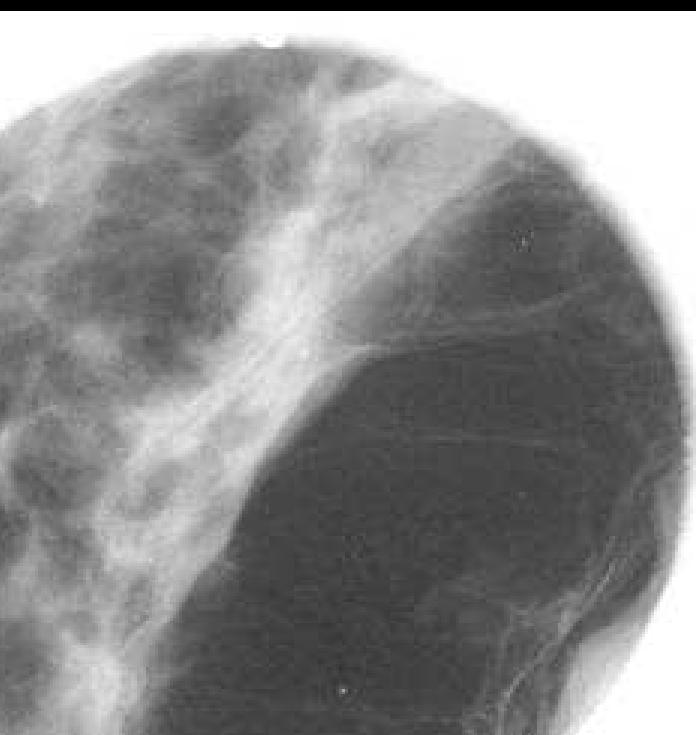
...: ultrahigh brilliance

10^{12} , 12 keV photons



- medical applications require photons above 20 keV
- smaller FELs (Undulator 20m) could fit into hospitals
- co-operation with ESRF on phase-contrast imaging studies

conventional X-ray
absorption



phase shifts much stronger than absorption

refractive index: $n = 1 - \delta - i\beta$

refraction $\sim E_{ph}^{-2}$

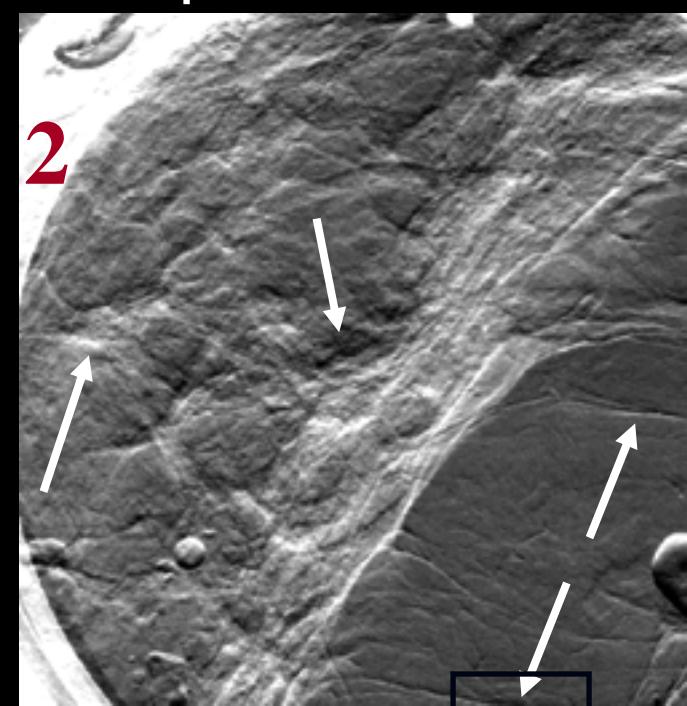
absorption

same w/ phase-contrast im



less dose

better
resolution



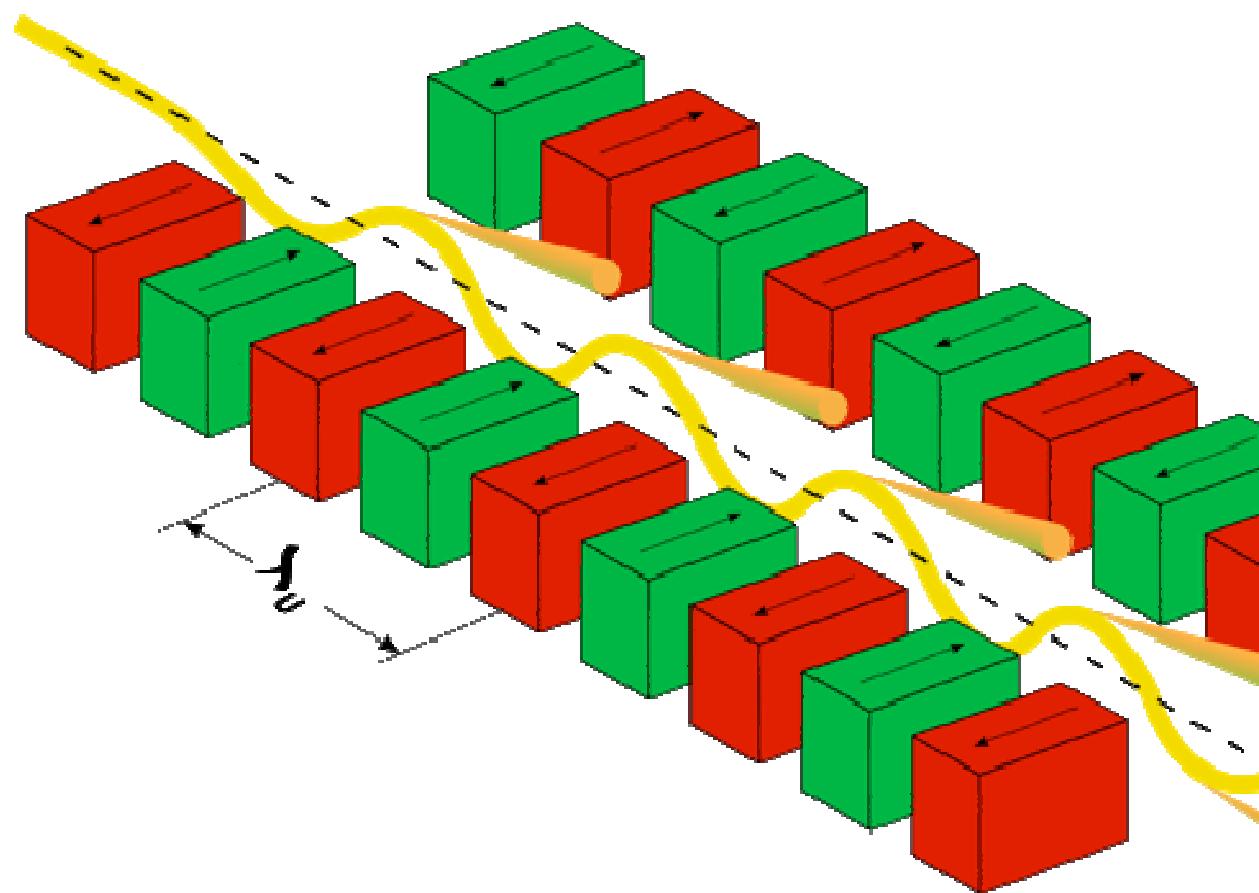


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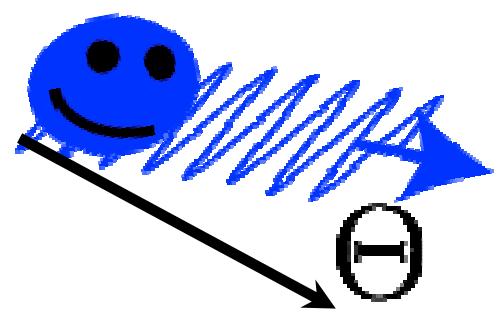
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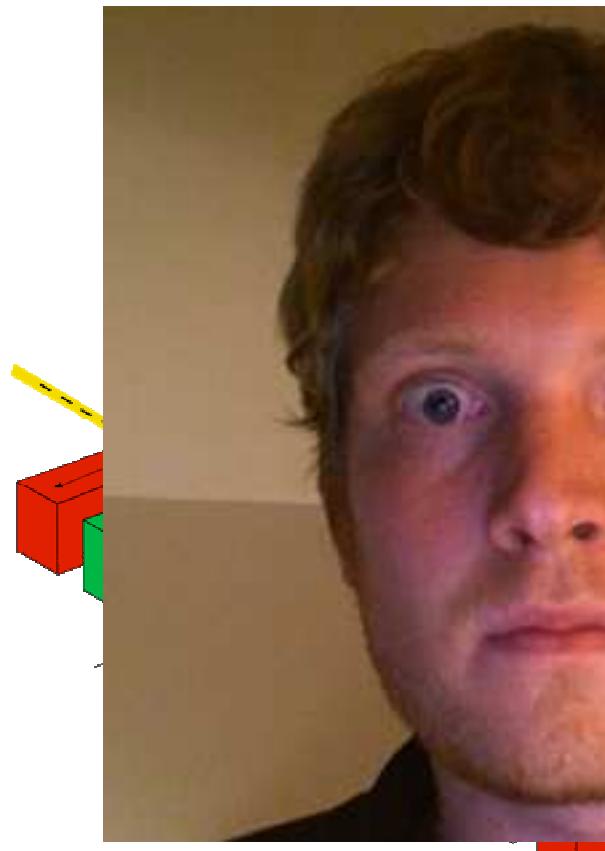


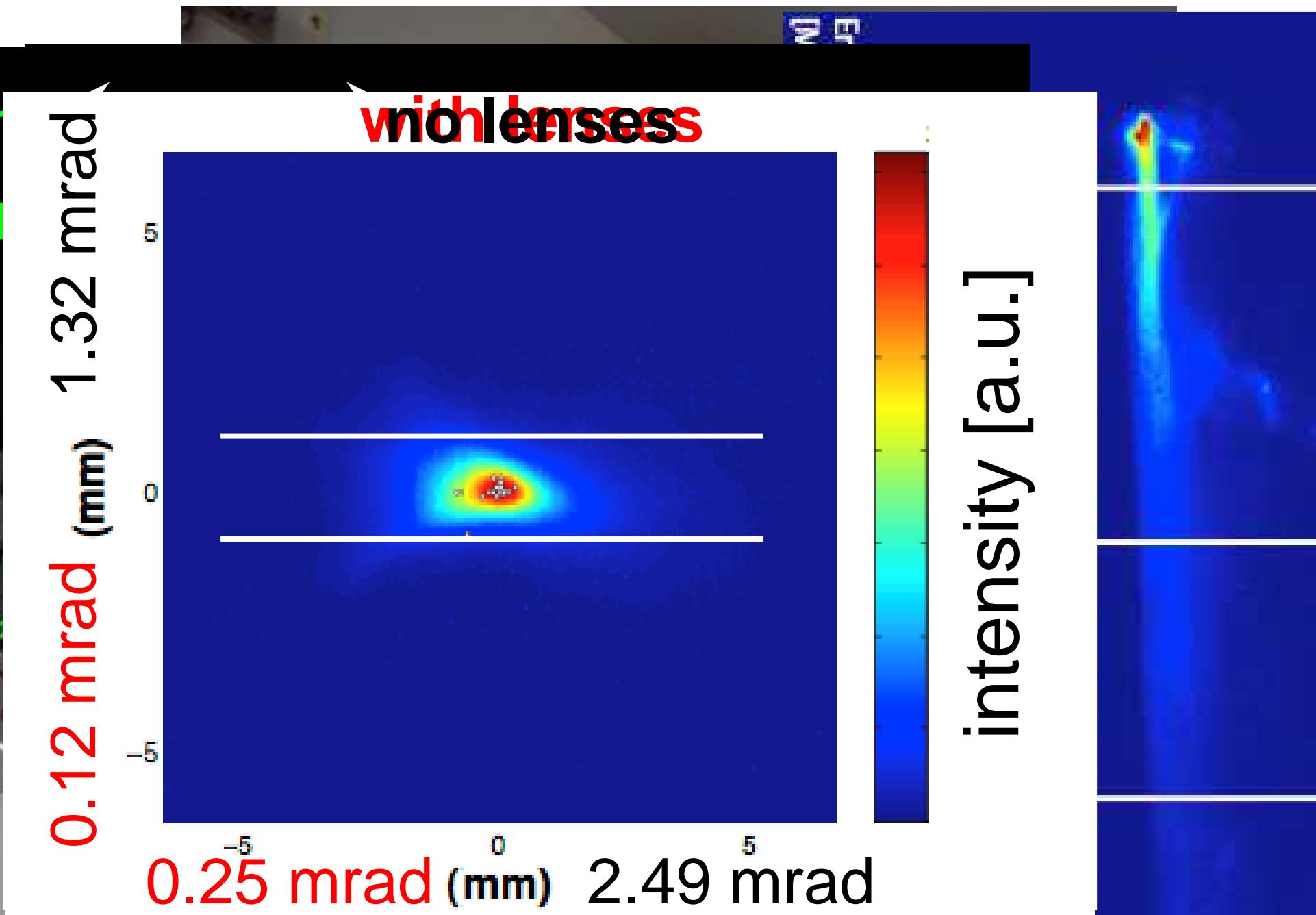
ndulator period: λ_u
agnetic field [on axis]: B
eflection parameter:
electron energy: γ

$$K \propto B \cdot \lambda_u$$



$$\frac{\lambda_{\text{res}}}{2\gamma^2 \Theta^2} \left(\left(1 + \gamma \frac{K^2}{2} \Theta^2 \right) - \gamma^2 \Theta^2 \right)$$





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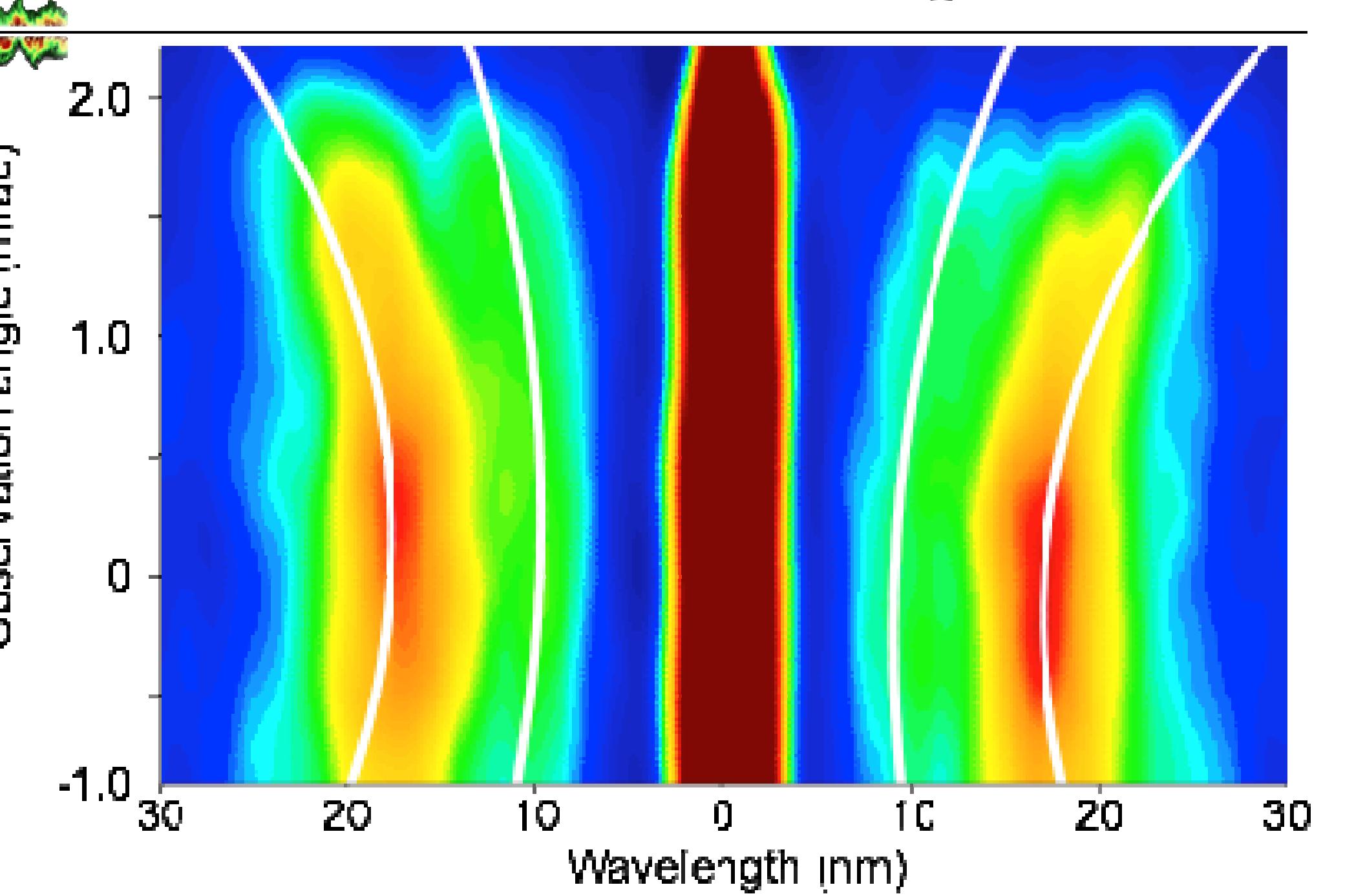
V

W

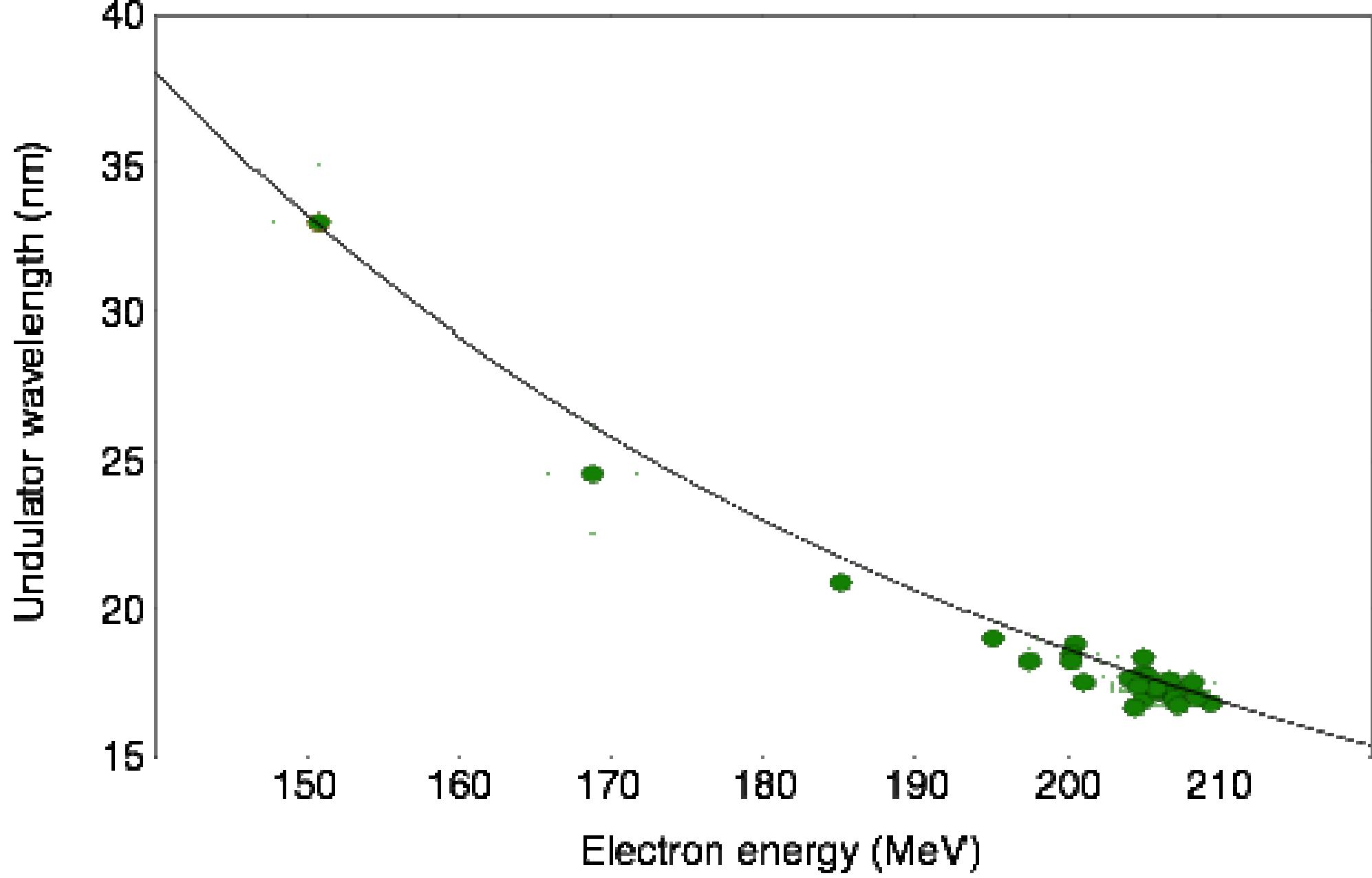
X

Y

Z

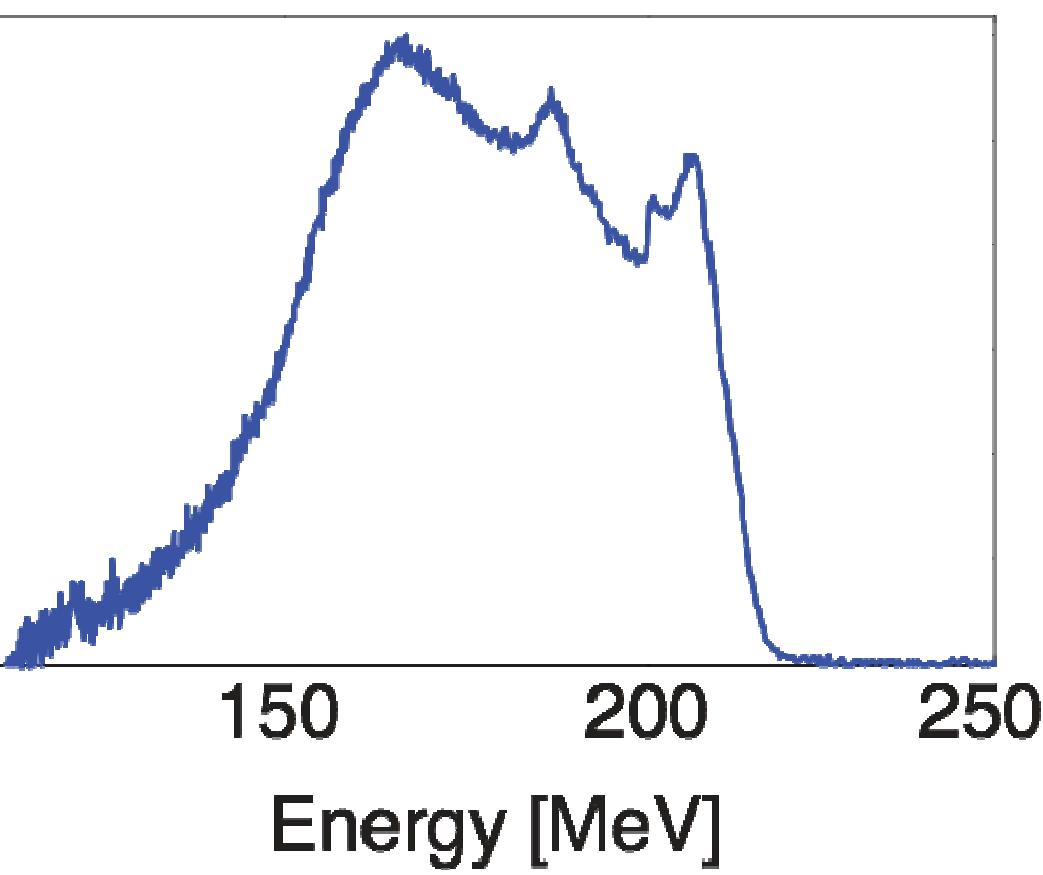


$$\lambda_{\text{res}} = \frac{\lambda_u}{2n\gamma^2} \left(1 + \frac{K^2}{2} + \gamma^2 \Theta^2 \right)$$

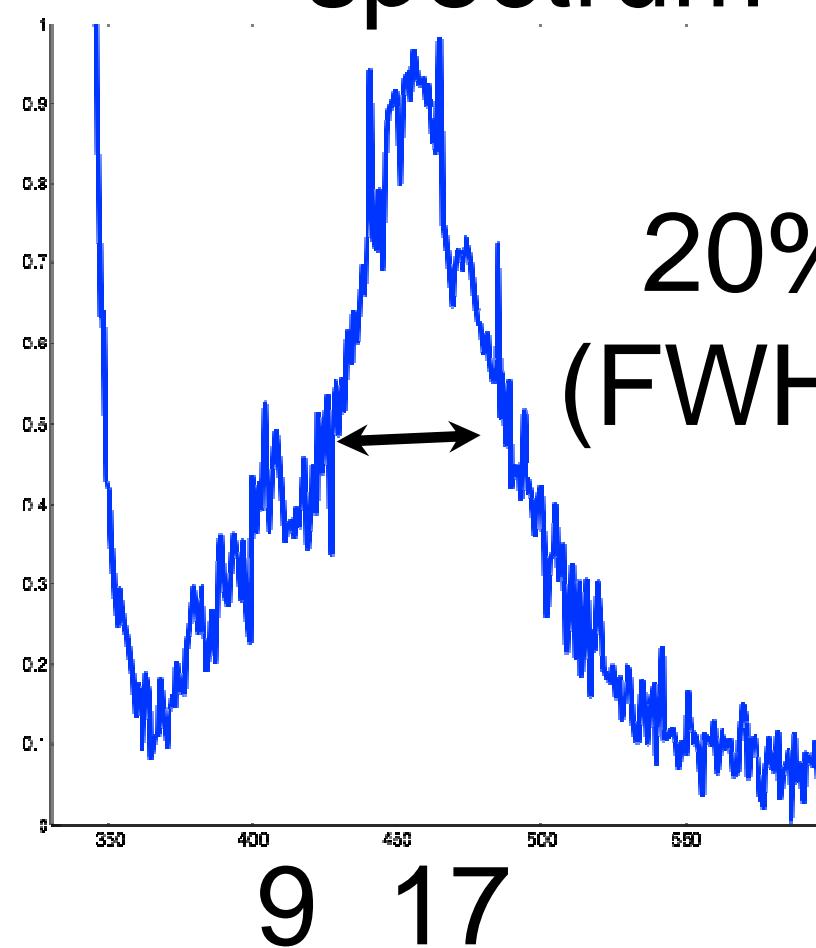


$$\lambda_{\text{res}} = \frac{\lambda_u}{\sqrt{1 - \frac{K^2}{2} + \gamma^2 \Theta^2}}$$

Electron spectrum



Undulator spectrum



20%
(FWH)

horizontal envelope $\sigma_{e,x}$

190 MeV

vertical envelope $\sigma_{e,y}$

7 8
1 m —————→

z

7 8

210 MeV

z

7 8

240 MeV

position
of CCD

undulator b

size:

$$\Sigma = \sqrt{\sigma_e^2(z) +$$

electron beam size
element

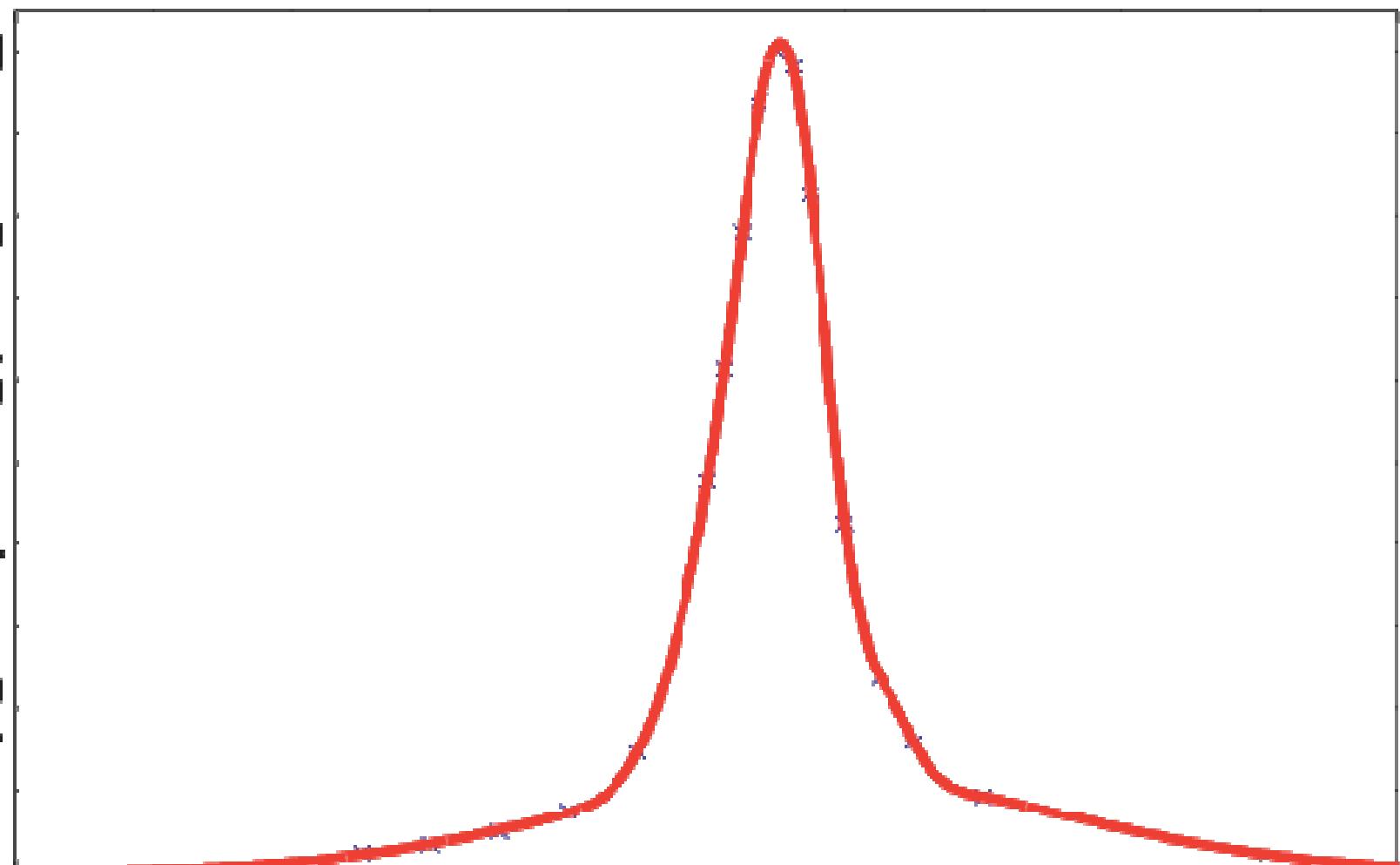


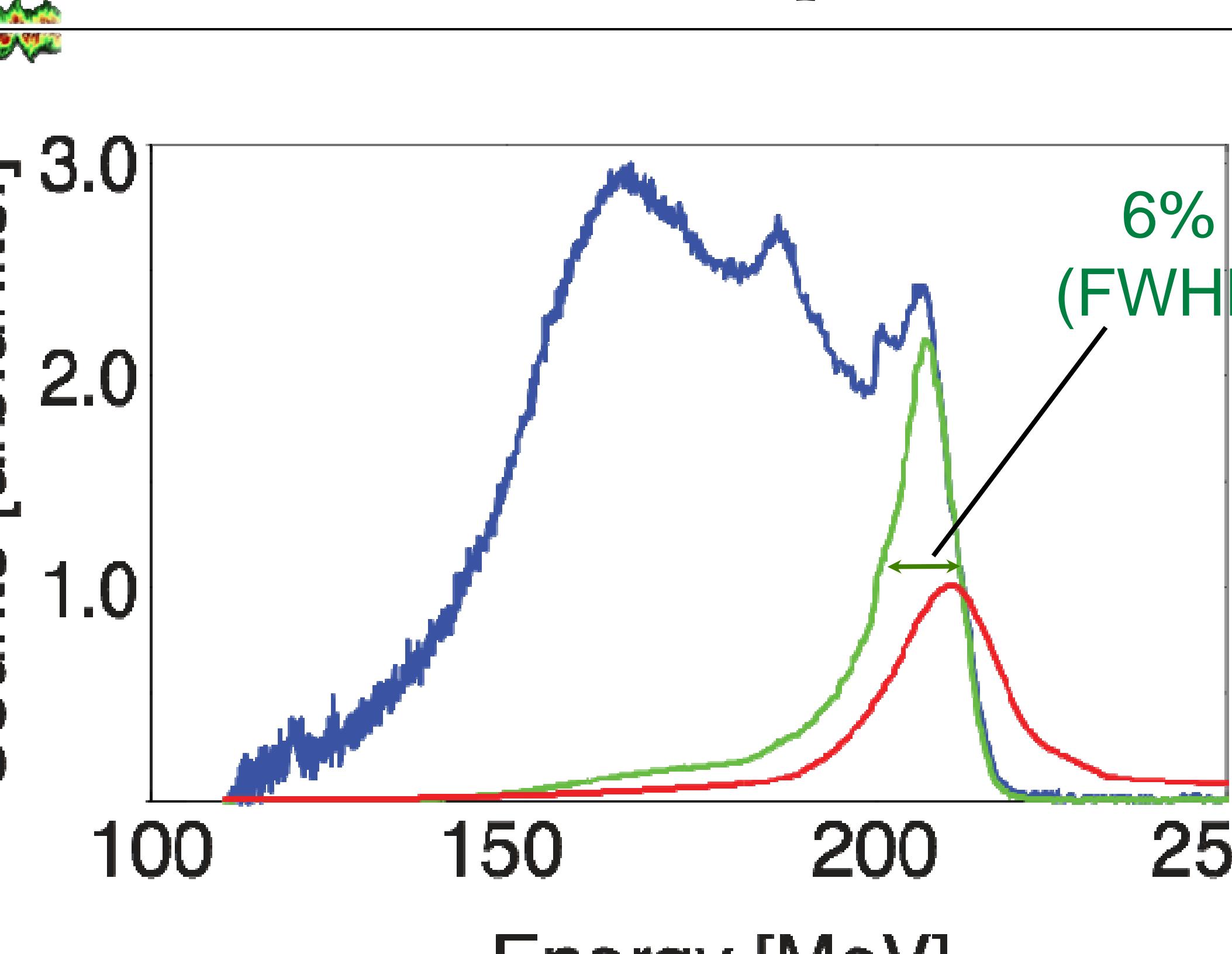
Normalized
On-axis flux [arb.units.]

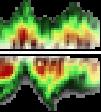
1.0
0.8
0.6
0.4
0.2

120 160 200 240 280

Energy [MeV]

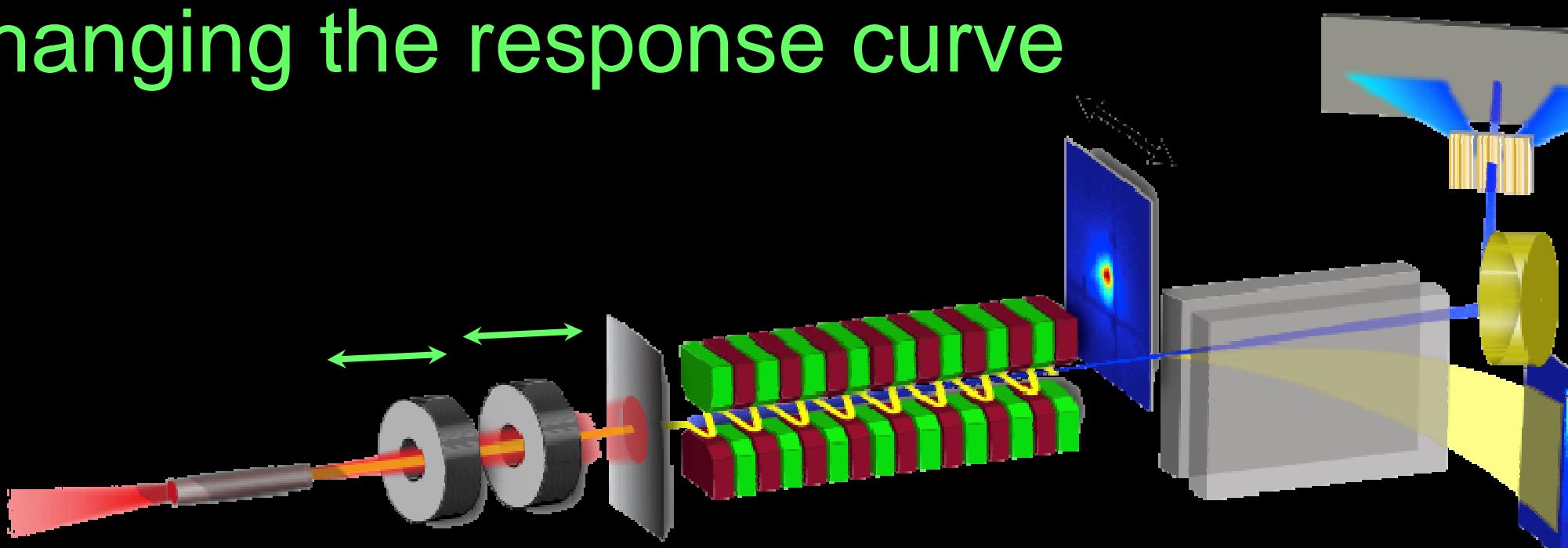


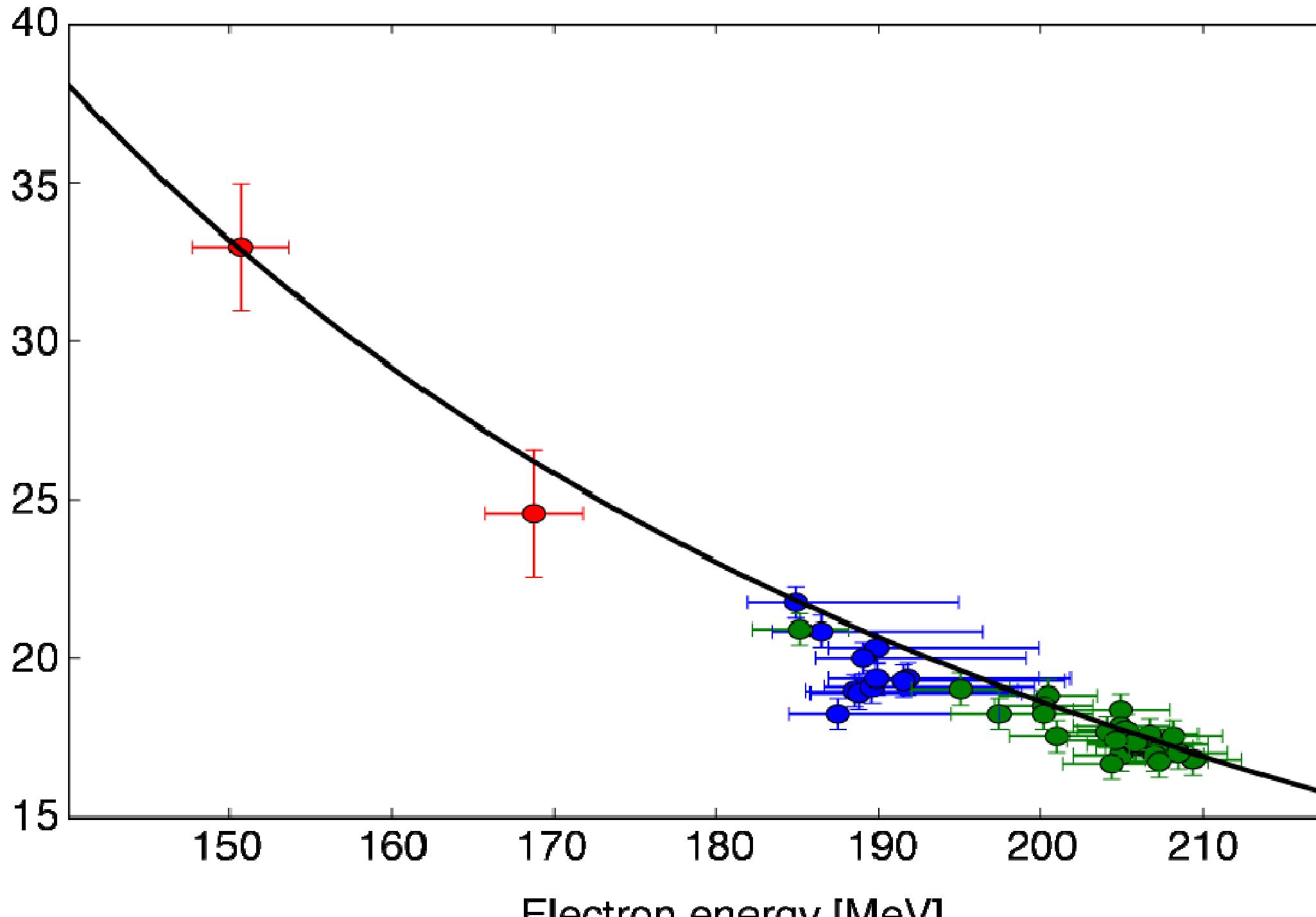


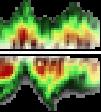


g by moving the lens' position:

changing the response curve







ation measured down to ~6 nm

le operation: detected undulator spectra in 70 % of
secutive laser shots

-to-shot wavelength variation of 5%

able in wavelength by changing lens' positions

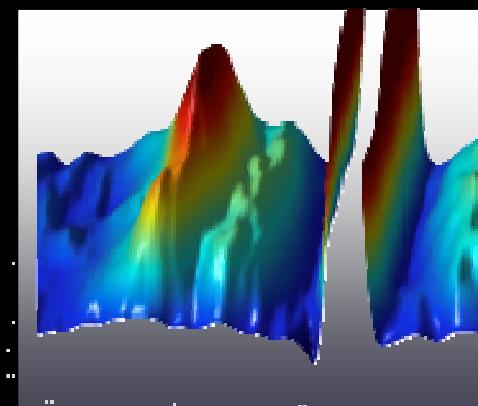
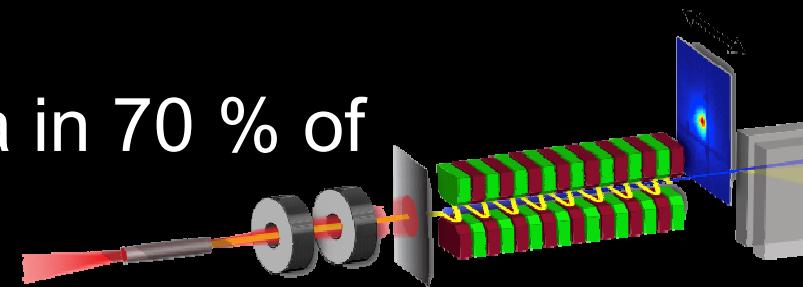
photons in the fundamental (whole CCD)

000 photons/(shot mrad² 0.1%b.w.) in 10 fs

ESSY femtoslicing: 1,000 photons in 100 fs]

ectly synchronized to the laser (pump-probe experiments)

e duration intrinsically few 10 fs (already spontaneous radiation)





short laser-driven hard-X-ray (incoherent)

undulator source:

higher electron energy: 1 GeV => ~1 keV

ns

charge: 1 pC => few 100 pC

numbers of photons independent of emitted
 $N \propto N_e \cdot N_u \cdot K^2$
energy:

increase undulator length (# periods), larger K

TEL:

above energy spread: < 0.5%

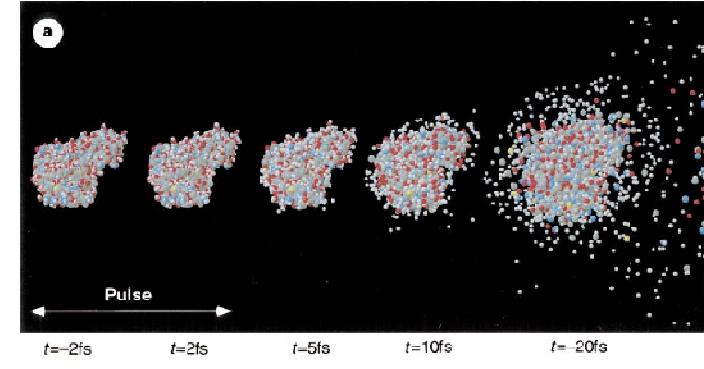
charge (few 100 pC)

higher electron energy

above beam optics & undulator design (cryo-cooled)



T. Meier, P. Pol
SCIENCE 308





higher electron energies: => plasma channel

LBNL, Berkeley

W.Leemans et al, N

Phys 2 (2006)

more charge/less energy spread: target engineering

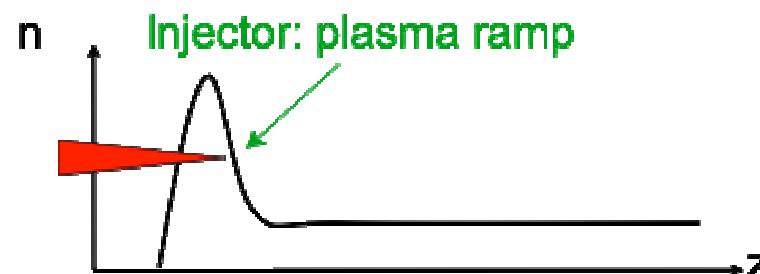
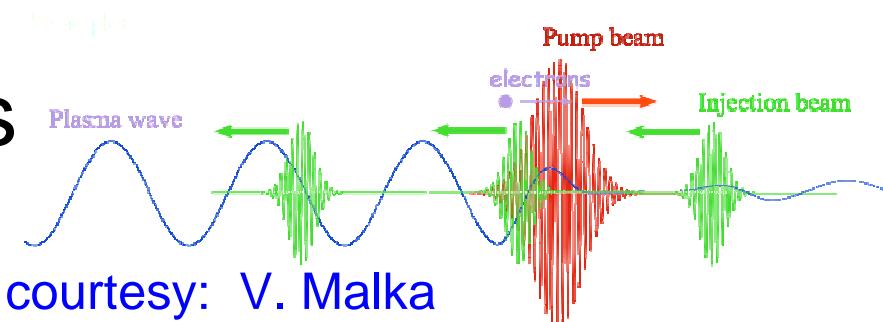
LOA: 1

energy

(10

C.Rechatin et
(20

counter propagating pulses



courtesy: W. Leemans

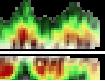
LBNL: 0.5-1 m
backside of
low longitudinal
transverse mo

C.Geddes e

(20

pulse shaping (low emittance, counteract beam
g)

AS laser system (MPO) has been upgraded (100 TW)



ultrashort
ray undulator source

(banquet) table-top FELs possible with plasma accelerators: peak current above current

world's first laser-driven soft-X-ray undulator source

stable electron acceleration at MPQ