Coherent Amplification of Ultrashort Pulses in a High-gain Medium: X-ray Lasers Seeded with High-Harmonic Pulses

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Motivation

X-ray/EUV pulses with excellent properties

Strong	for high SNR and nonlinear optics
Ultrashort	for temporal resolution
Coherent	for phase control and ultimate resolution
Polarized	for quantum state specification
X-ray/EUV	for spatial resolution

Applications

Time-resolved spectroscopy/microscopy:
Investigation of material structure/dynamic at (sub)fs and nm
Ex). Attoscience, coherent diffraction imaging, …

Practical X-ray Sources

Source	Scheme	Coherence	Characteristics	Reference
X-ray laser	Laser plasma, discharge plasma	Y	5 ps, 10-50 nm, narrowband, µJ, laser rep. rate or kHz	Suckewer, Laser Phys. Lett. **6**, 411 (2009)
Atomic HH	Laser plasma	Y	<100 fs, 10-60 nm, broadband, <µJ, laser rep. rate	Krausz, Rev. Mod. Phys. **81**, 163 (2009)
XFEL	Accelerator	Y	10-500 fs, ~ nm, mJ, 100 Hz	Websites of European XFEL and LCLS
Hard x-ray from cluster/liquid/solid	Laser plasma	N	<ps, 0.1 nm, 10^{10} photons (4pi sterad), kHz	Attwood, Soft X-rays and Extreme Ultraviolet Radiation (1999)
Synchrotron	Accelerator	N	100 ps, >0.1 nm, 100 MHz	Attwood, Soft X-rays and Extreme Ultraviolet Radiation (1999)

Coherent X-ray/EUV Sources

Topic of this talk

	High harmonics	X-ray laser	X-ray free electron laser
Wavelength	10 ~ 60 nm (broad frequency comb)	10 ~ 50 nm (narrow spectrum $\triangle\lambda/\lambda$~10^{-5})	> 0.1 nm (broad frequency comb)
Polarization	Linearly polarized	Randomly polarized	Linearly polarized
Energy/pulse	pJ ~ sub μJ/order (10^6 ~ 10^9 photons/shot)	μJ (10^{10} ~ 10^{12} photons/shot)	mJ
Pulse duration	<= 30 fs	> ps	10-500 fs
Coherence	Highly coherent	Limited spatial coherence	Limited temporal coherence
Mechanism	Nonlinear oscillation forced by optical laser	Quantum laser with bound electrons ASE (laser plasma): out of random spontaneous emission	Classical laser with free electrons SASE (accelerator): out of noise
	Seed	**X-ray/EUV amplifier**	

HH Seeding of XRL

Research questions

HH seeding of XRL for
strong ultrashort coherent polarized x-ray/EUV source?

How is it different from optical amplification?
– physics of amplification of ultrashort x-ray/EUV pulses in a high-gain medium

Experimental reports

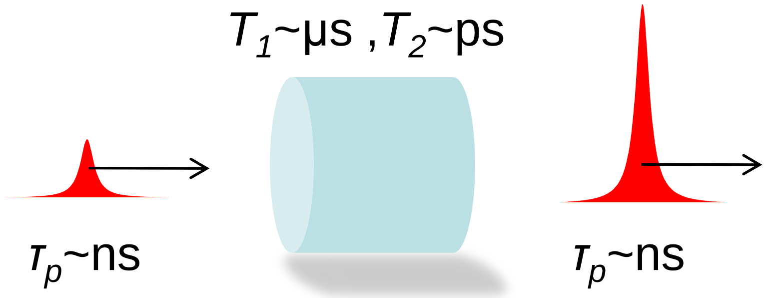
Zeitoun et al., Nature **431**, 426 (2004).
Wang et al., Nature Photon. **2**, 94 (2008).

Optical Amplification vs HH Amplification

Optical amplification

$Ti{:}Al_2O_3$ @ 820 nm

T_1~μs , T_2~ps



Broad gain bandwidth $\Delta\lambda \sim 50\,\mathrm{nm}$

Low gain (weak ASE) g_0~1 cm^{-1}

Incoherent amplification $T_2 \ll \tau_p \ll T_1$

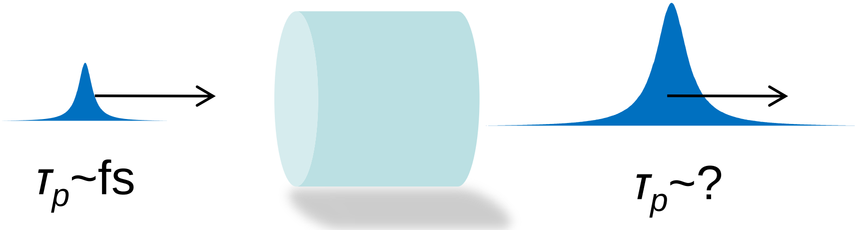
Frantz-Nodvik (FN) equations

intensity and population

HH amplification

Ni-like Ag (Ag^{19+}) @ 13.9 nm

T_1~ps , T_2~ps



Narrow gain bandwidth $\Delta\lambda \sim 10^{-3}\,\mathrm{nm}$

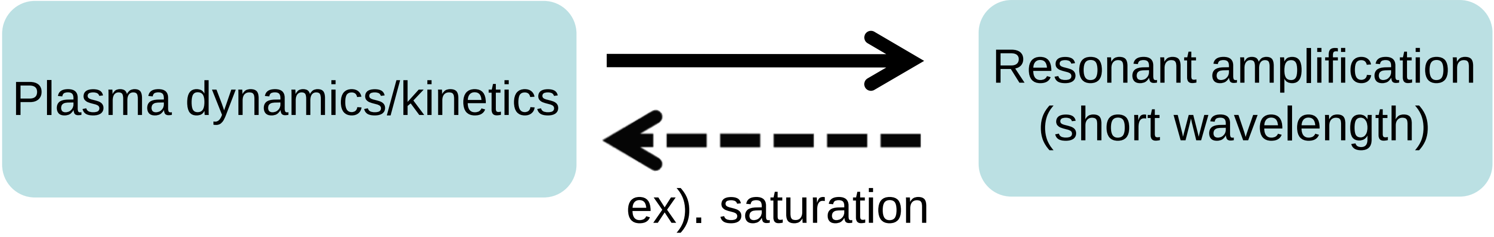
High gain (strong ASE) g_0~80 cm^{-1}

Coherent amplification $\tau_p \ll T_1, T_2$

Maxwell-Bloch (MB) equations

field, population, and dipole

Theoretical Description



Plasma dynamics/kinetics

Resonant amplification
(short wavelength)

ex). saturation

Hydrodynamic equations

FN or MB equations

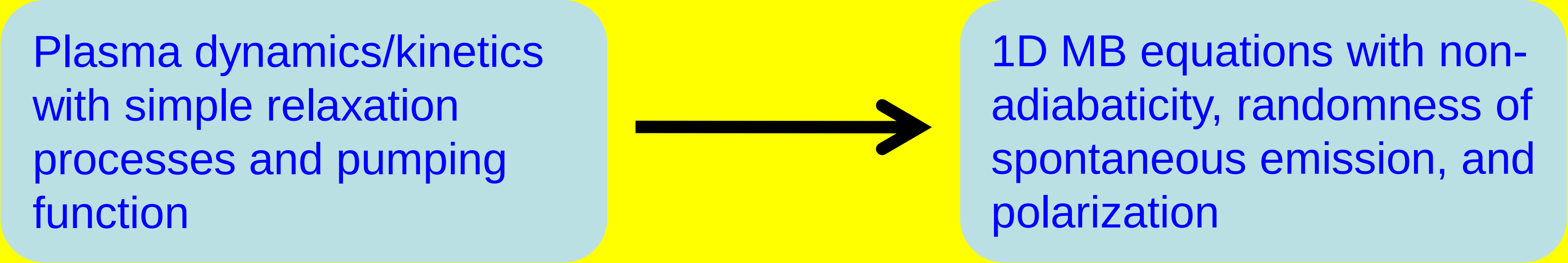
Frantz-Nodvik equations

Wang et al., Nature Photon. **2**, 94 (2008)

Maxwell-Bloch equations

Al’miev et al., Phys. Rev. Lett. **99**, 123902 (2007)
Robillart et al., X-Ray Lasers 2008
Variation in treating adiabaticity, randomness of spontaneous emission, polarization, dimensions, and plasma dynamics/kinetics

Our approach

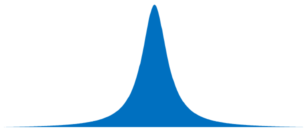


Plasma dynamics/kinetics with simple relaxation processes and pumping function

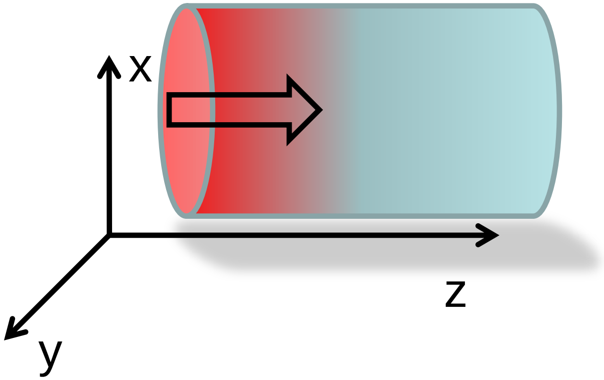
1D MB equations with non-adiabaticity, randomness of spontaneous emission, and polarization

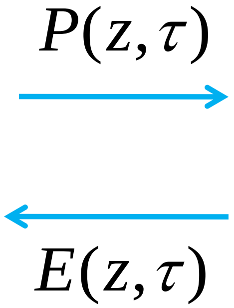
Theoretical Model

Atoms pumped synchronously with HH pulse
(ideal traveling-wave amplification)
Ag^{19+}: 4d → 4p (13.9 nm)



High harmonic pulse
(13.9 nm, x-pol. , 25 fs, 1 nJ, 400 μm^2)





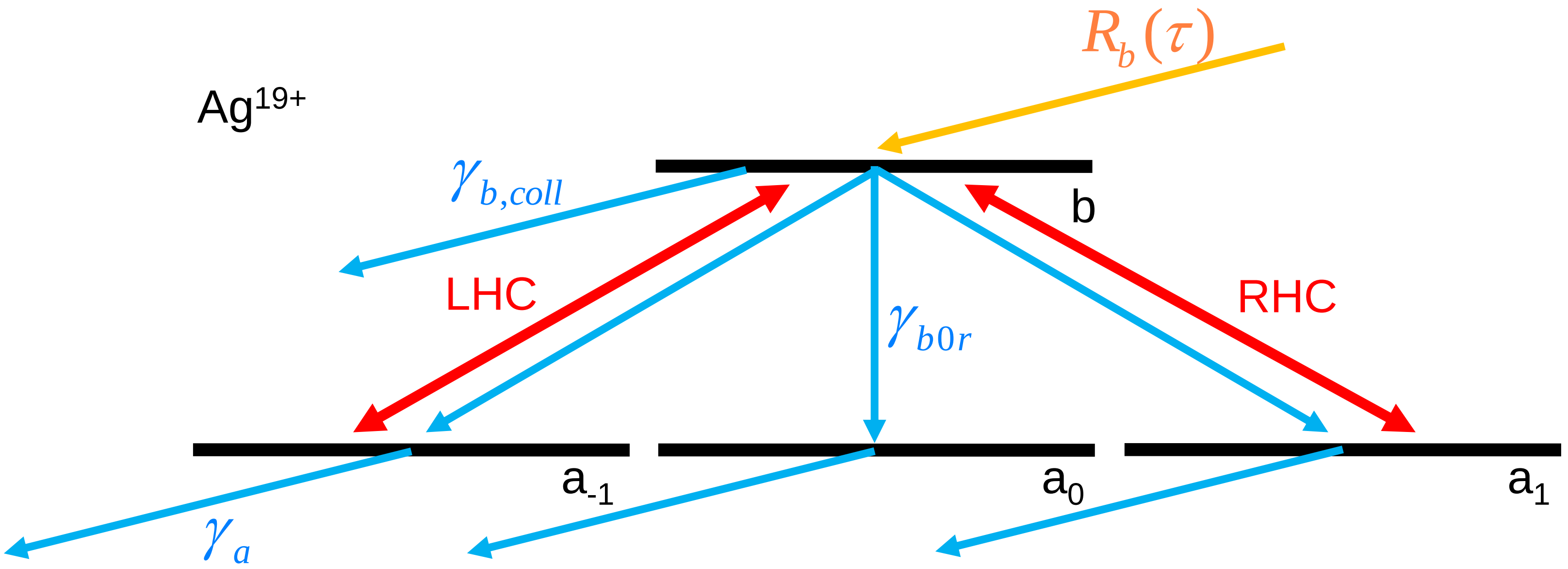
$$P(z,\tau)$$

Atomic response
Bloch equations
(time domain)

Field evolution
Maxwell equation
(space domain)

$$E(z,\tau)$$

Two-level four-state atom



Level b: 3d^9 4d: $^1S_0$ (m=0)

Level a: 3d^9 4p: $^1P_1$ (m=-1,0,1)

→ pumping (collisional)

→ decay (radiative/collisional)

↔ lasing transition

Practically, a Λ system with pumping and decay
The states of the degenerate lower level should be separately treated.

Shore, The Theory of Coherent Atomic Excitation
Hasegawa et al., J. Opt. Soc. Korea **13**, 60 (2009)

Maxwell-Bloch equations

Eq. for populations

$$\dot{N}_b = -\gamma_b N_b + \mathrm{Im}\left\{P_R E_R^* + P_L E_L^*\right\}/2 + R_b$$

$$\dot{N}_{a1} = -\gamma_a N_{a1} + \mathrm{Im}\left\{P_R^* E_R\right\}/2 + \gamma_{bir} N_b$$

$$\dot{N}_{a,-1} = -\gamma_a N_{a,-1} + \mathrm{Im}\left\{P_L^* E_L\right\}/2 + \gamma_{bir} N_b$$

Eq. for polarizations

$$\dot{P}_R = -\gamma_{ba1} P_R - i z_{ba}^2 \left\{E_R \cdot \left(N_b - N_{a1}\right) + n_i \rho_{-1,1} E_L\right\} + \Gamma_R$$

$$\dot{P}_L = -\gamma_{ba1} P_L - i z_{ba}^2 \left\{E_L \cdot \left(N_b - N_{a,-1}\right) + n_i \rho_{1,-1} E_R\right\} + \Gamma_L$$

$$n_i \dot{\rho}_{1,-1} = -\gamma_{1,-1} n_i \rho_{1,-1} + i\left\{P_R^* E_L - P_L E_R^*\right\}/4$$

Eq. for electric fields

$$\partial E_L / \partial z = \left(i 2\pi \omega_0 / c\right) \cdot \left(P_L - n_e E_L / \omega_0^2\right)$$

$$\partial E_R / \partial z = \left(i 2\pi \omega_0 / c\right) \cdot \left(P_R - n_e E_R / \omega_0^2\right)$$

$R_b(\tau)$ pumping to the upper level

$\Gamma_{L,R}(N_b, \tau)$ random source of spontaneous emission

Larroche et al., PRA **62**, 043815 (2000)
Shore, The Theory of Coherent Atomic Excitation

Parameters

$$\hbar\omega_0 = 89.2\,\mathrm{eV}\,(\lambda_0 = 13.9\,\mathrm{nm})$$

From EHYBRID (laser-plasma simulation)

$$\gamma_a = 2.33\times10^{12}\ \mathrm{Hz}\ (1/\gamma_a = 0.429\,\mathrm{ps})$$

$$\gamma_b = 2.56\times10^{12}\ \mathrm{Hz}\ (1/\gamma_b = 0.391\,\mathrm{ps})$$

$$n_e = 2.0\times10^{20}\ \mathrm{cm}^{-3}$$

$$g_{0,\max} = 70\,\mathrm{cm}^{-1} \Rightarrow n_{i,\max} = 9.05\times10^{15}\ \mathrm{cm}^{-3}$$

From MCDFGME (atomic calculation)

$$\gamma_{bir} = 5.93\times10^{10}\ \mathrm{Hz}\ (1/\gamma_{bir} = 16.9\,\mathrm{ps})$$

$$z_{ba} = 0.274\,\mathrm{au}$$

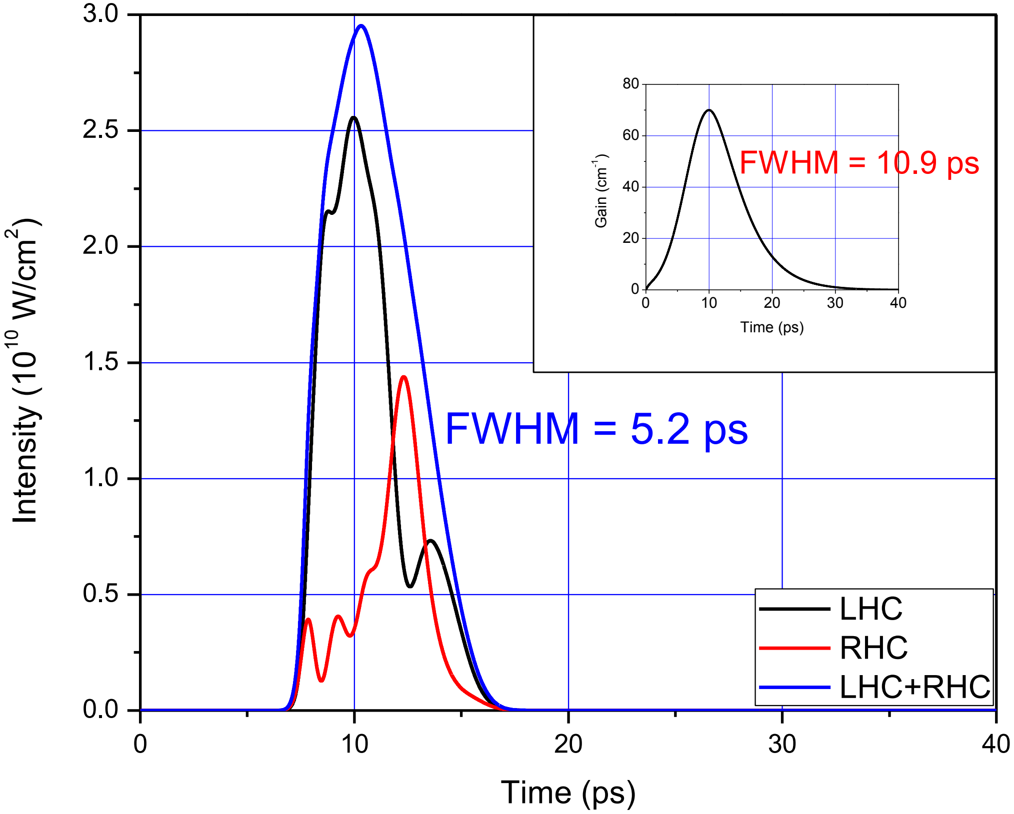
From typical experimental report

$$\gamma_{ba} = 3.39\times10^{12}\ \mathrm{Hz}\,(1/\gamma_{ba} = 0.295\,\mathrm{ps}, \Delta\lambda/\lambda = 5\times10^{-5})$$

$$\gamma_{1,-1} = 3.27\times10^{12}\ \mathrm{Hz}\,(1/\gamma_{1,-1} = 0.306\,\mathrm{ps}, \gamma_{1,-1coll} = \gamma_{ba,coll}\ \text{assumed})$$

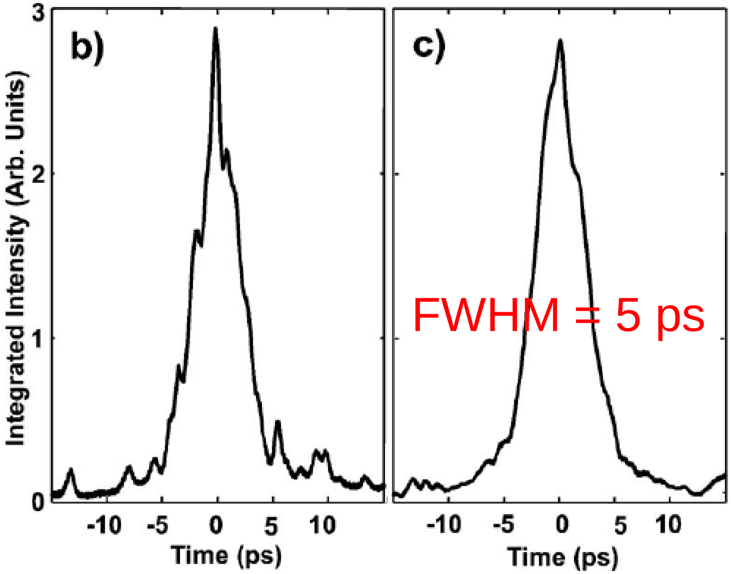
Relaxation rates > HH pulsewidth: coherent amplification

ASE XRL Pulse



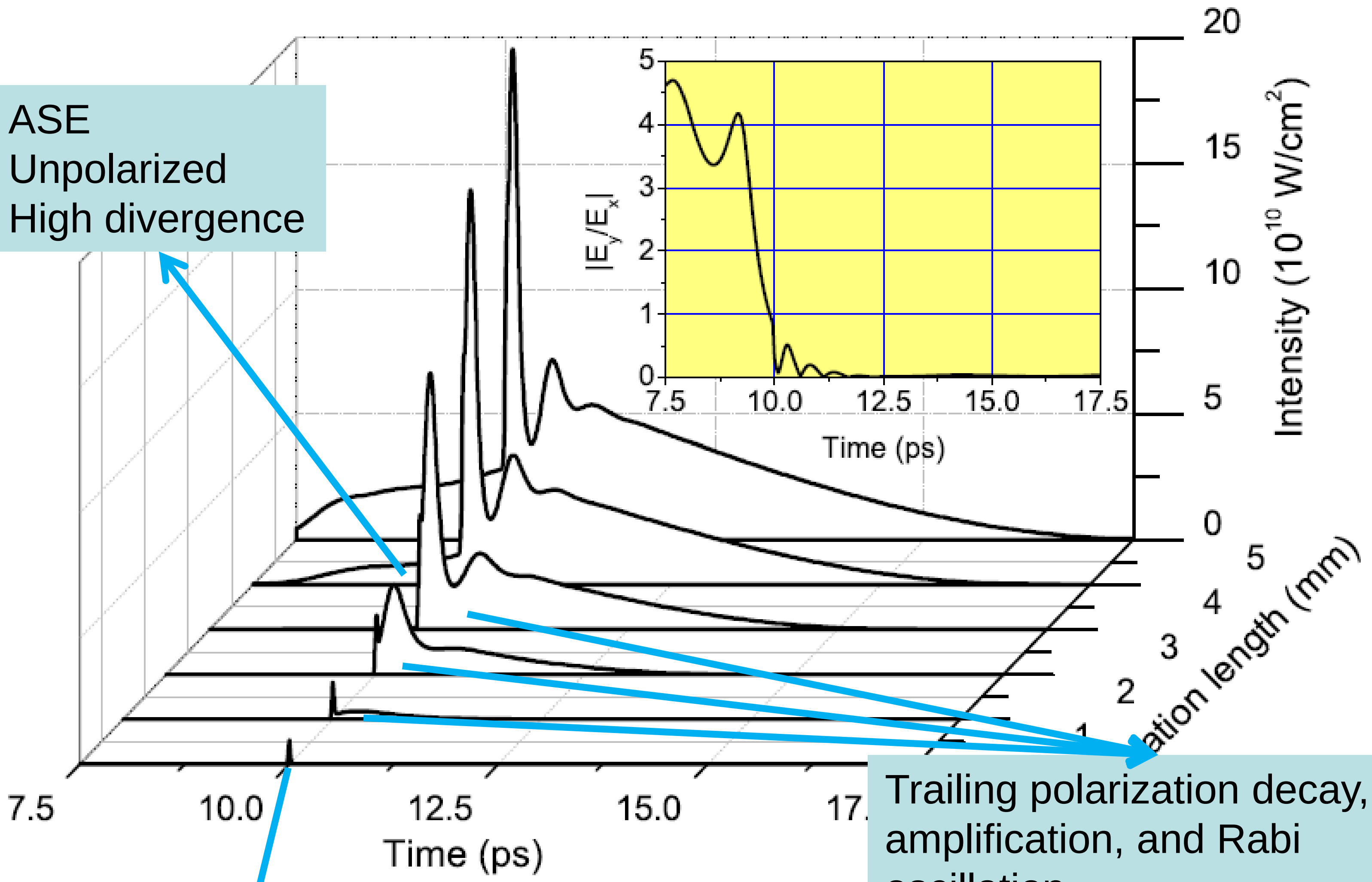
No input harmonic pulse; pure ASE
Propagation length = 5 mm
Time-dependent gain from EHYBRID

cf. Experimental Measurement



From Larotonda et al., Opt. Lett. **31**, 3043 (2006)

Key Result: HHseeded XRL Pulse



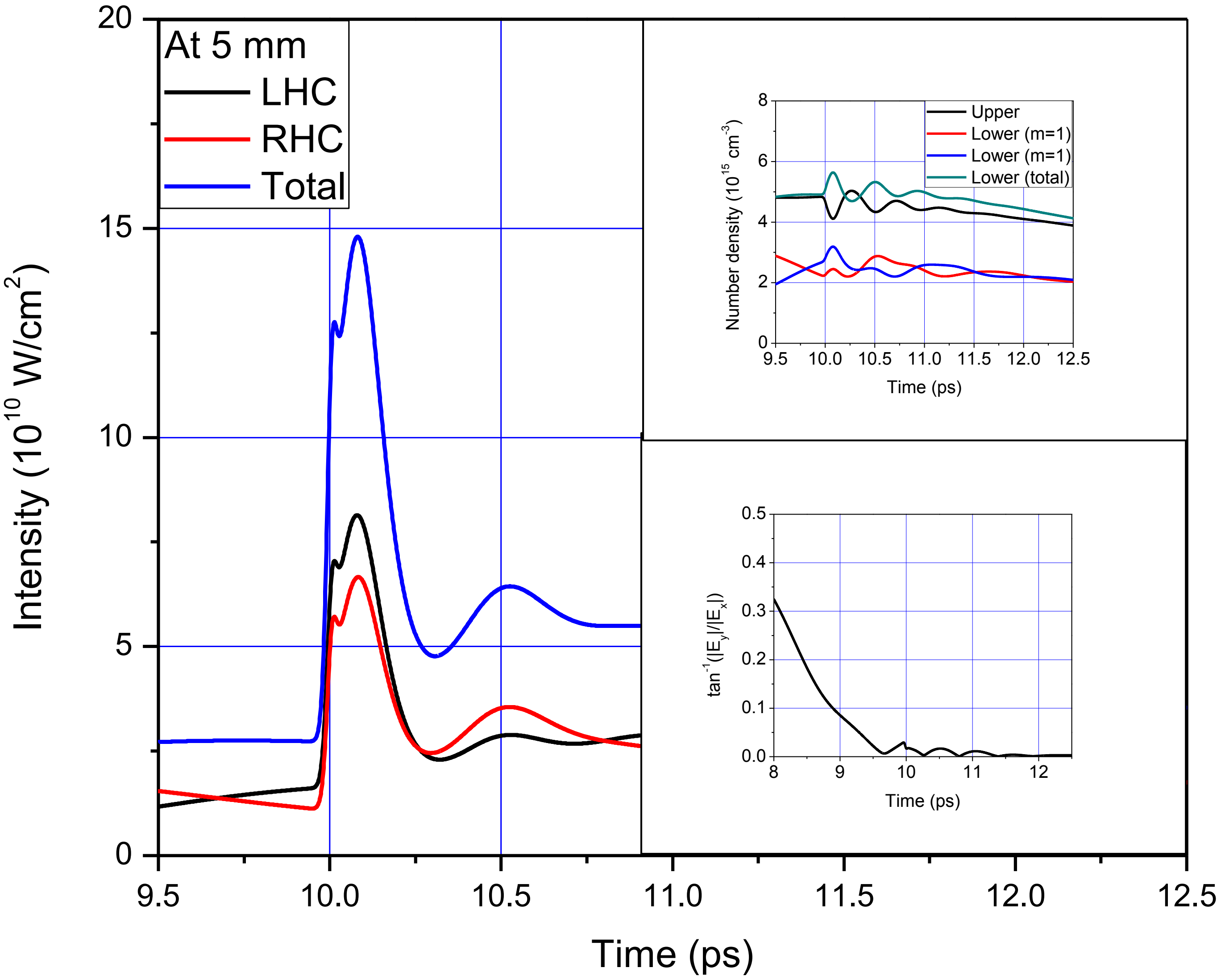
ASE
Unpolarized
High divergence

Trailing polarization decay, its amplification, and Rabi oscillation
Linearly polarized
Low divergence

Input harmonic pulse
gaussian 25 fs, 1 nJ

C. M. Kim et al., PRL **104**, 053901 (2010)
C. M. Kim et al., PRA **80**, 053811 (2009)

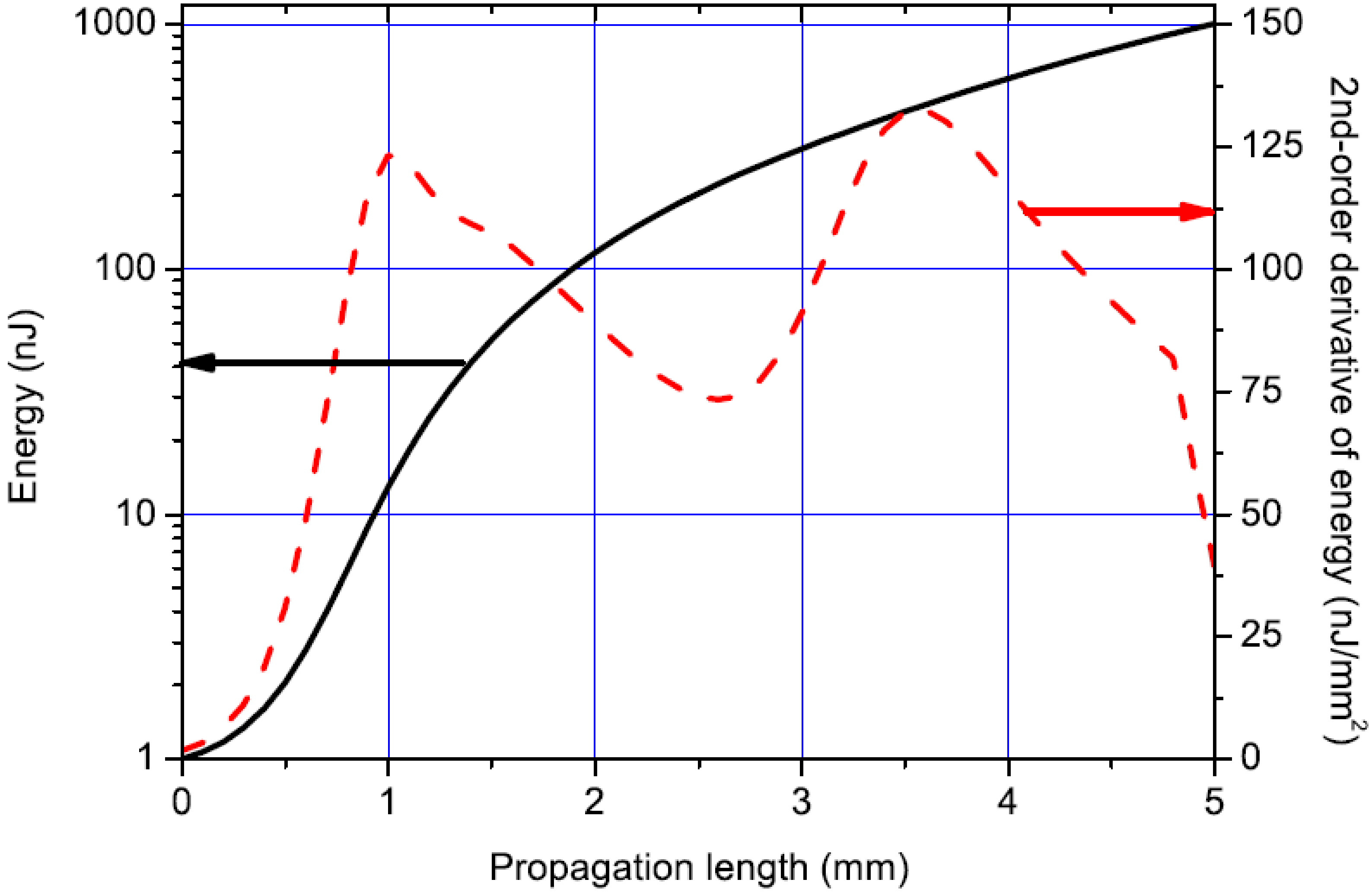
Rabi Oscillation (Saturation)



Energy of amplified HH << Energy of trailing coherent pulse

→ pulse width >= ps

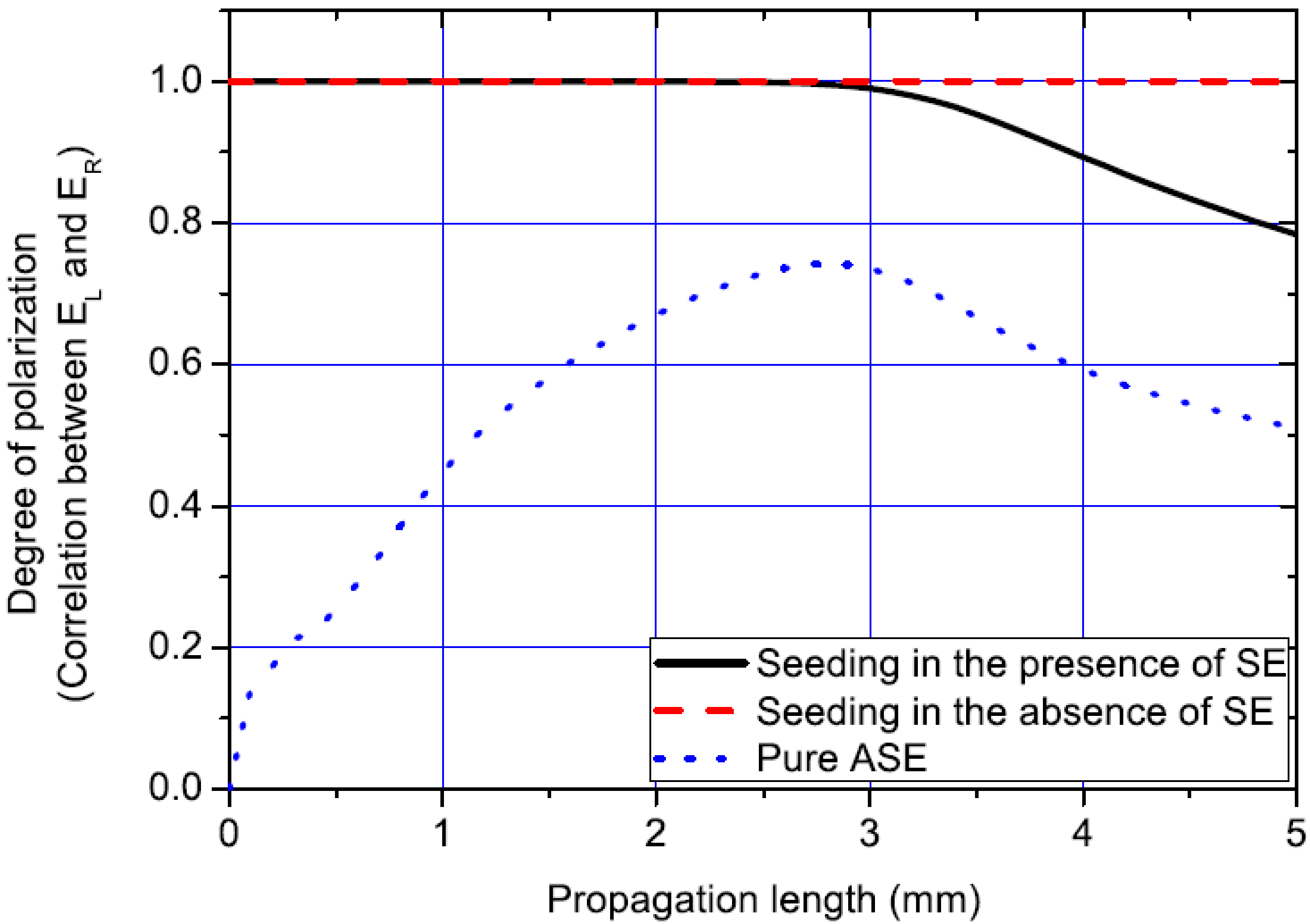
Amplification



Two saturations: one from coherent part and the other from ASE

For definition of saturation onset point, Imesch et al., X-Ray Lasers 2008

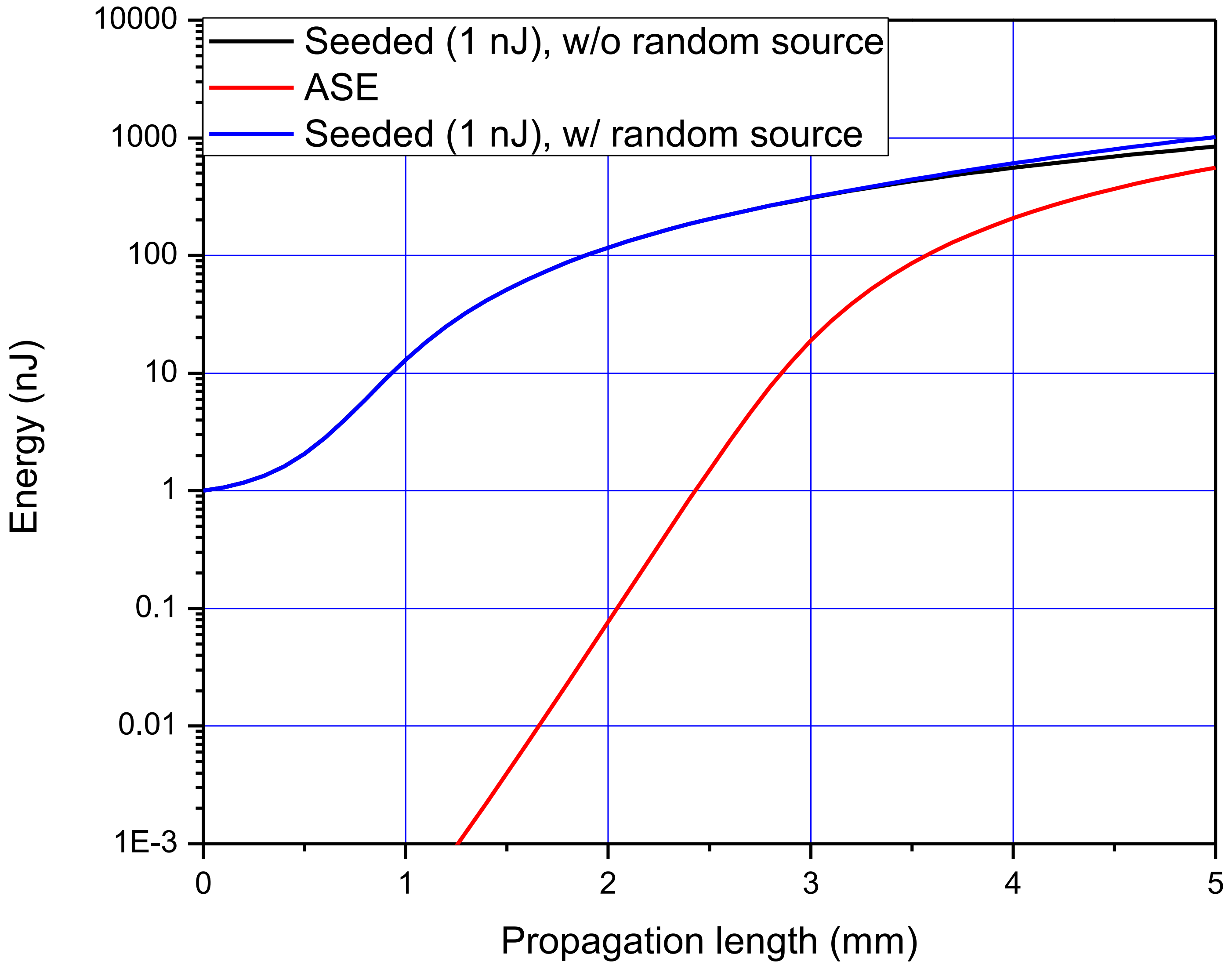
Degree of Polarization



Within a limited medium length, almost completely polarized.

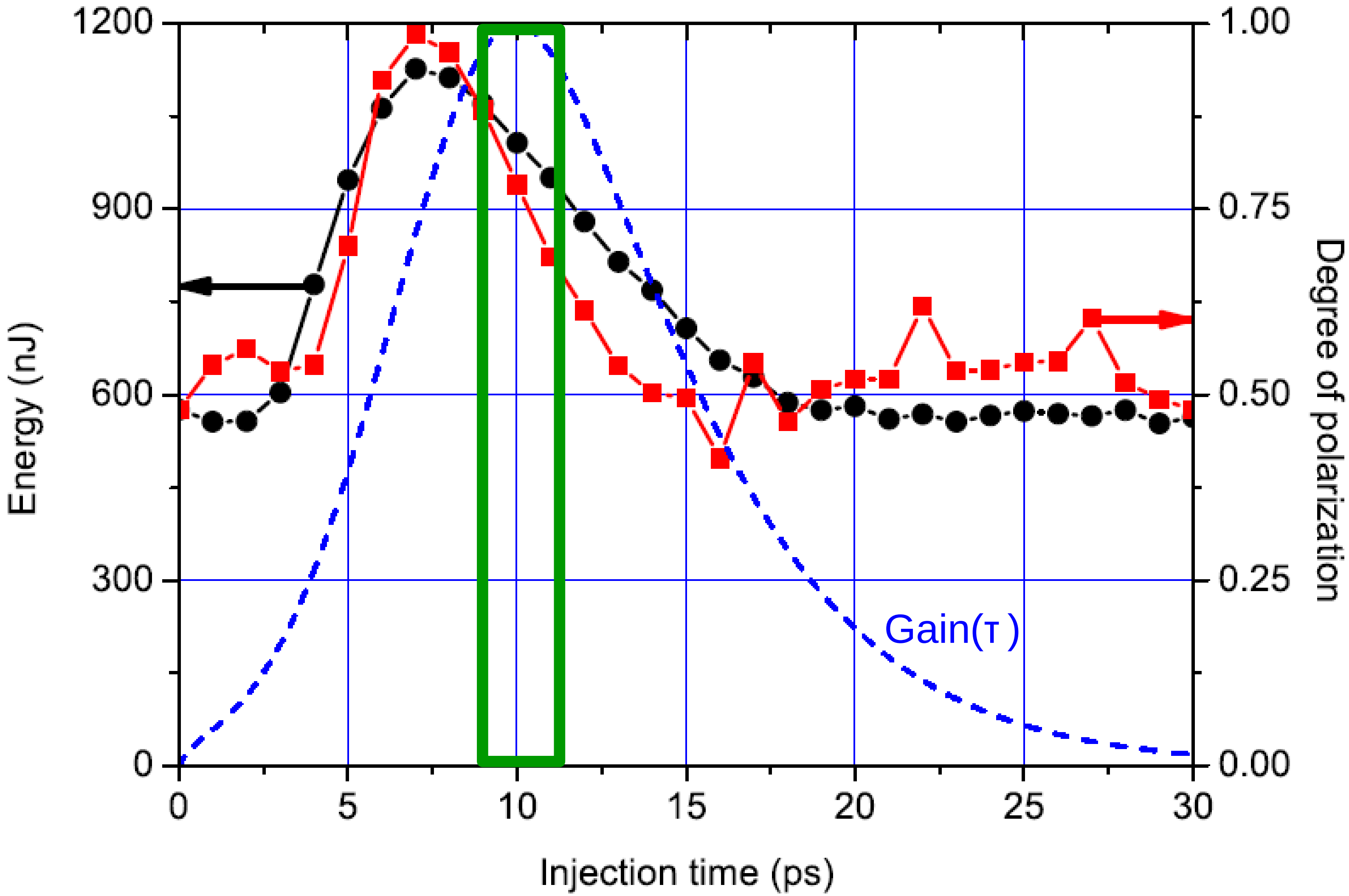
ASE reduces degree of polarization.

Amplification vs Harmonic Energy



Once saturated, no significant difference in energy extraction

Injection Time Optimization



Adjustment of injection time brings stronger and more polarized radiation.

Conclusion

HH seeding of XRL or XFEL for
strong ultrashort coherent polarized x-ray/EUV source?

Not for energy but for intensity

< ps for main peak

expected

expected

How is HH amplification different from optical amplification?

Strong ASE and narrow gain bandwidth restricts pulsewidth, coherence, and polarization.

How can we mitigate the restriction?

Make the interaction coherent as long as possible.

1. Adjustment of HH injection time
2. Multiple HH injection

Multistage Amplification

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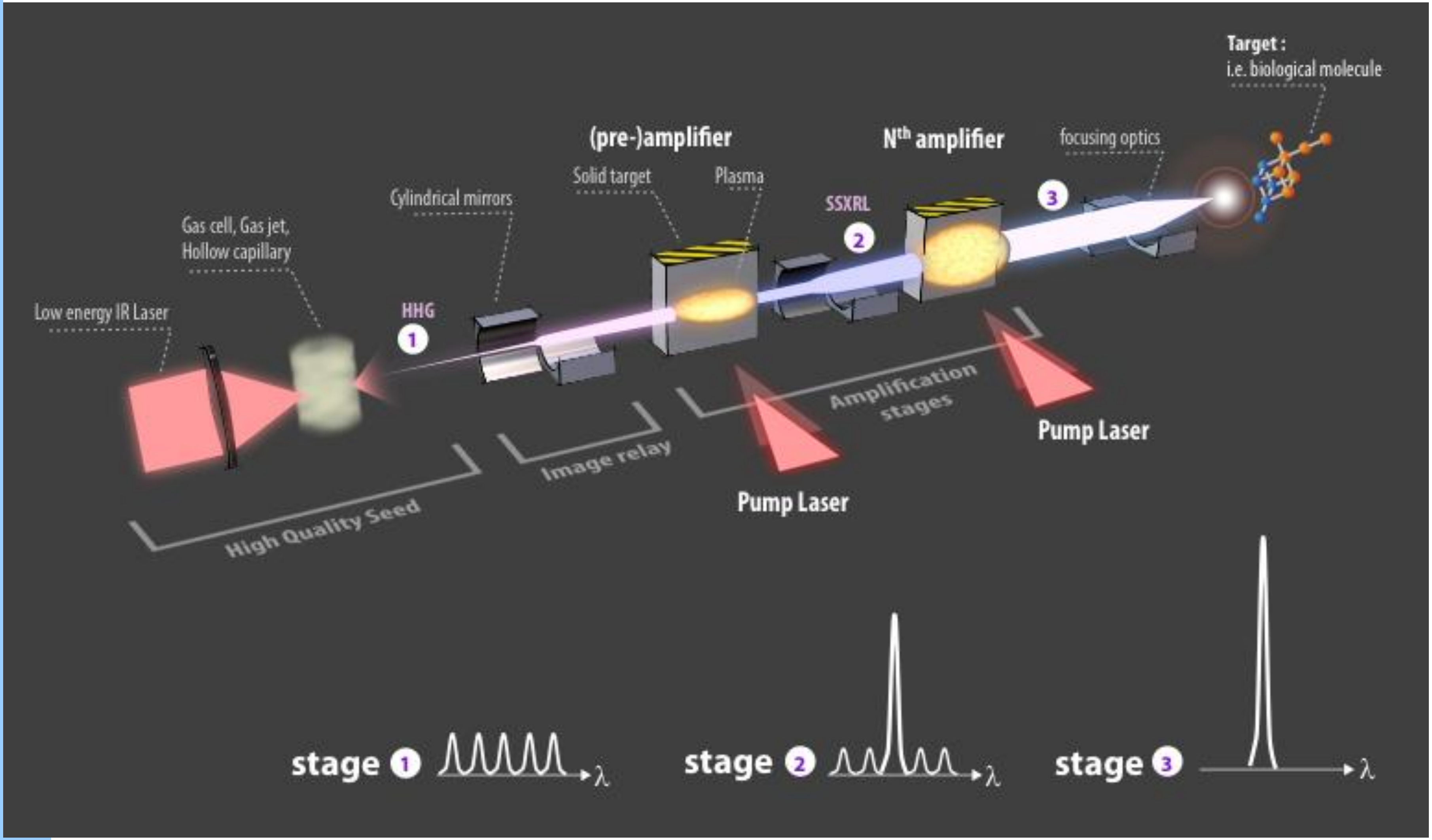
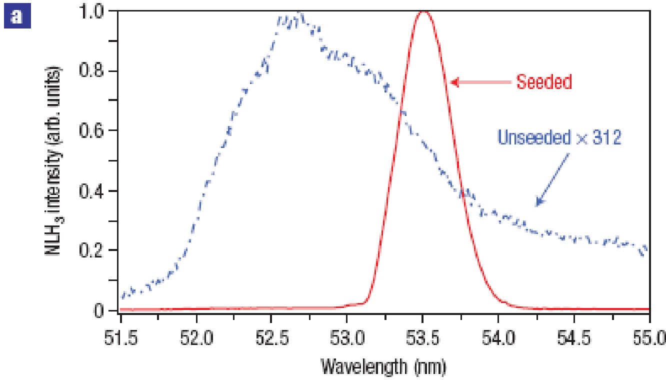
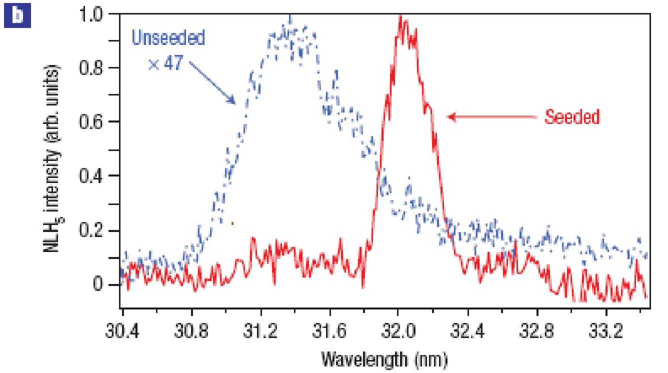


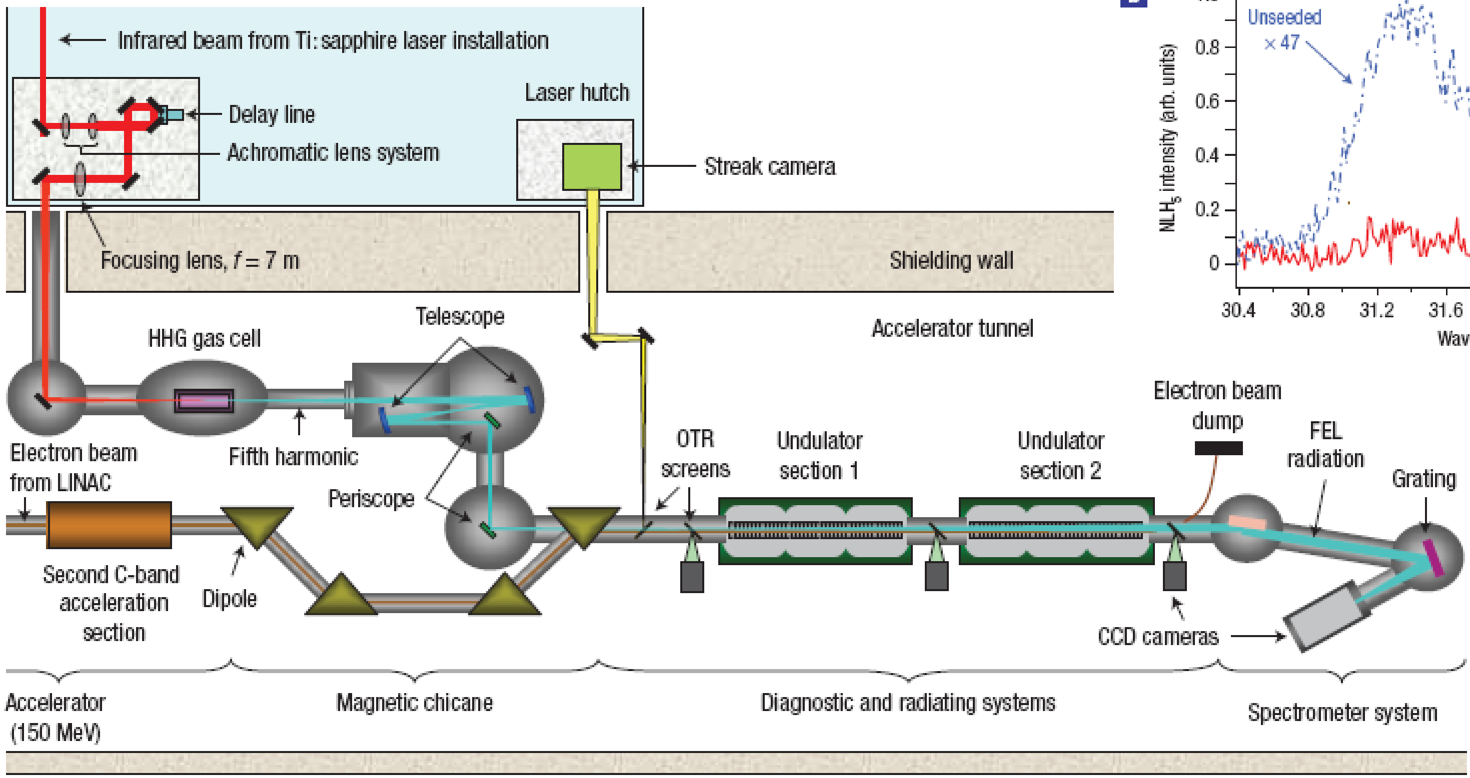
Courtesy of P. Zeitoun

HHseeded XFEL

HH seed pulse may improve longitudinal coherence and pulse energy.







Lambert et al., Nature Phys. **4**, 297 (2008).