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High harmonics from gas, a suitable source for seeding FEL from vacuum-ultraviolet to soft X-ray region (XUV)

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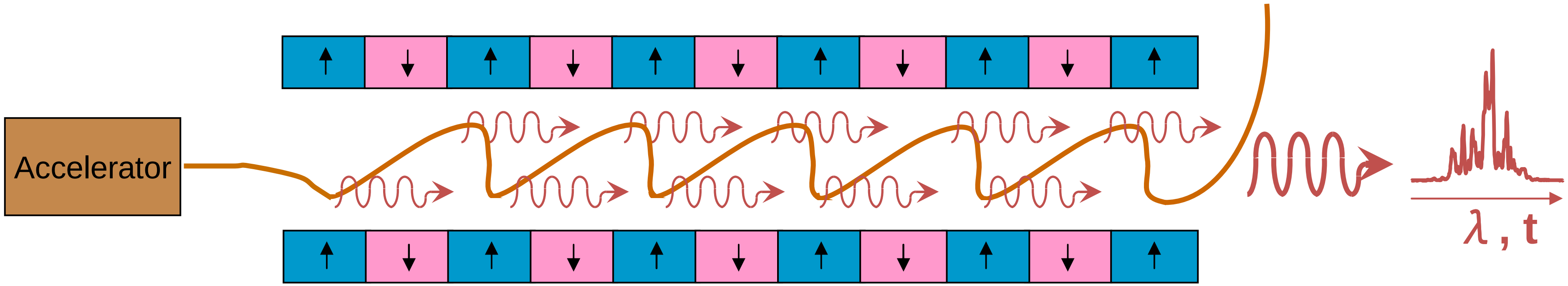
XUV Free Electron Lasers (FEL) : SASE

FLASH (2004, down to 4.1 nm), SCSS (2007, 50 nm), SPARC (2009, 160 nm)…

SASE: Self Amplified Spontaneous Emission



-High number of photon : 10^{12} photons
-Short pulse duration (sub ps)
peak power (GW)
-Relatively high repetition rate (tens Hz)
-High wavelength tuning
-Variable polarization
-Good wavefront *(Bachelard, PRL 106, 2011)*
-Good spatial coherence *(Ischebeck, NIMA 507, 2003)*

very performing tool for user experiment but…

SASE limitations

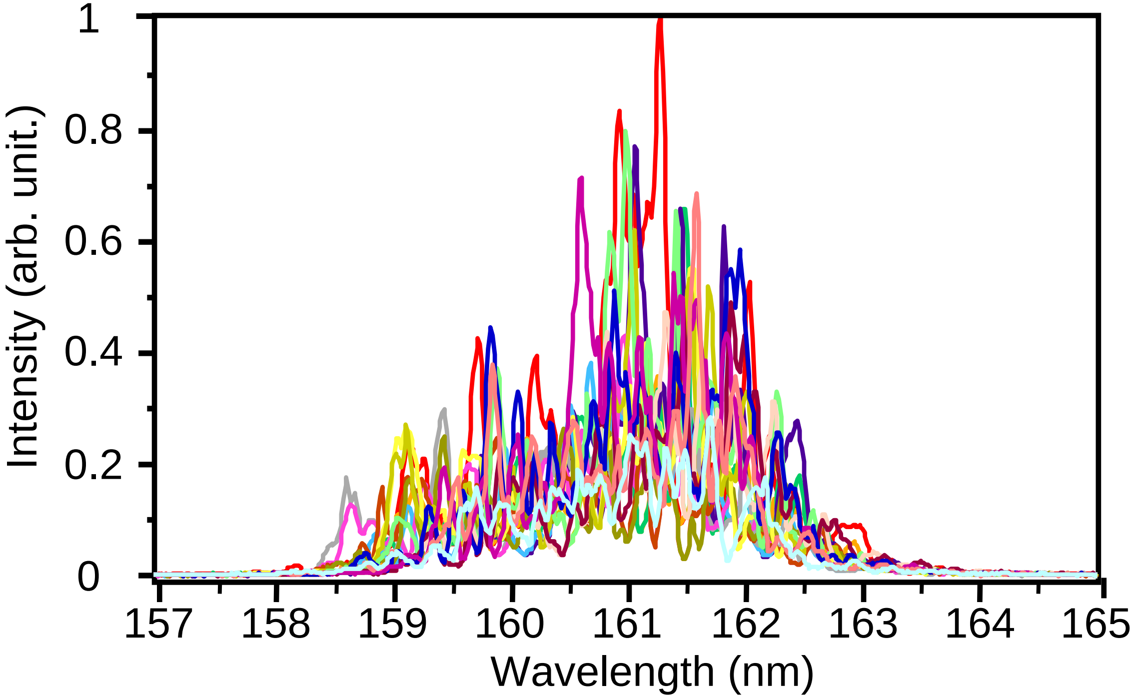
-Weak gain at short wavelength, single pass

long undulator (tens m)

-Relatively important shot to shot variations: intensity, temporal/spectral profile

jitter for pump-probe experiments

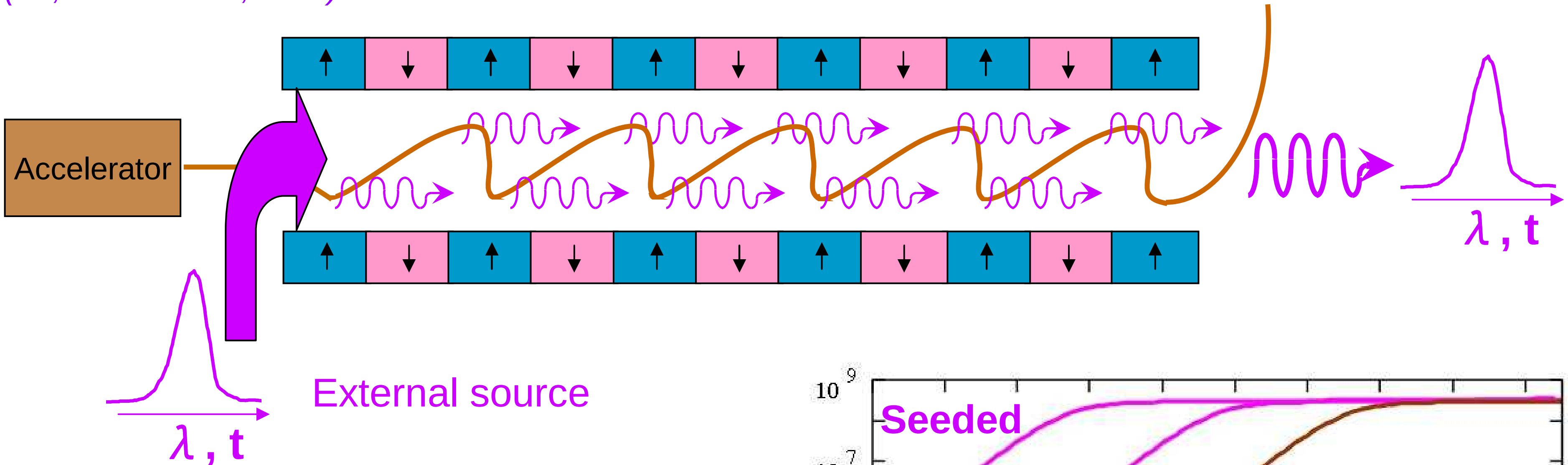
limited temporal coherence *(Saldin, Opt. Commun. 202, 2002)*



How to reduce/supress SASE limitations: “seeding fully coherent light” in XUV ?

Previous demonstrations in IR with CO_2 and Ti: Sa lasers, then in UV with crystals

(Yu, Science 289, 2000)



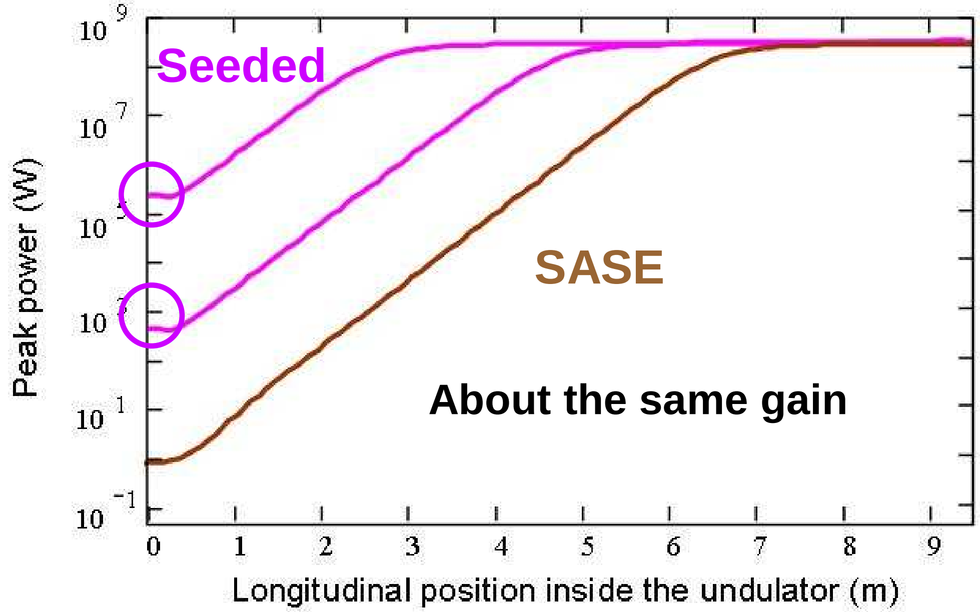
-Coherent

Improvement of the temporal coherence

-Intense

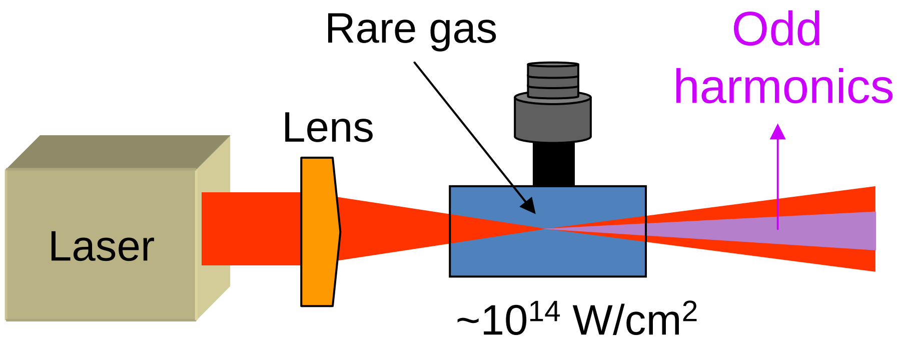
Decreasing of the saturation length

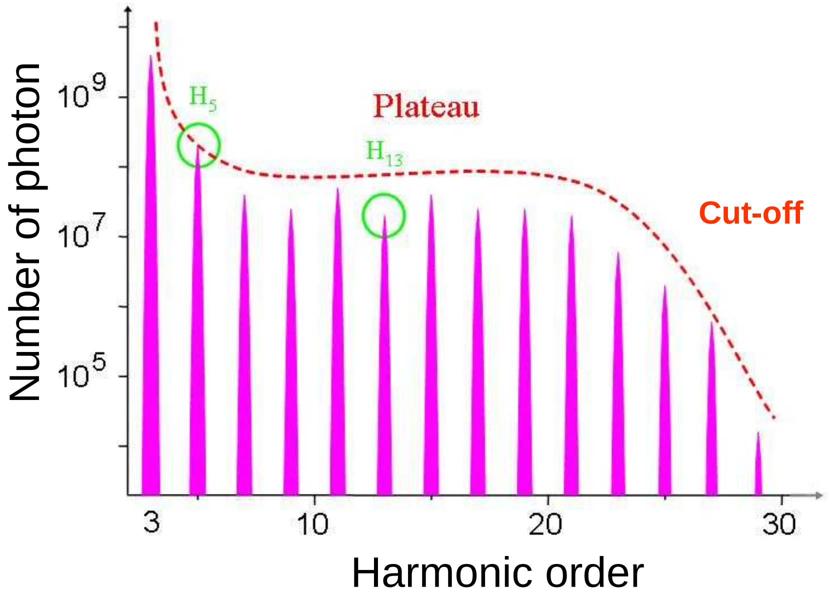
=> shorter undulator



XUV radiation : Harmonics produced from gas (HHG)

Why proposing High Harmonics Generated in gas (HHG) ?





- Spatially and temporally coherent
- Relatively tunable
- Short pulse duration (10-100 fs)
- Conversion efficiency (10^{-5} to 10^{-7})

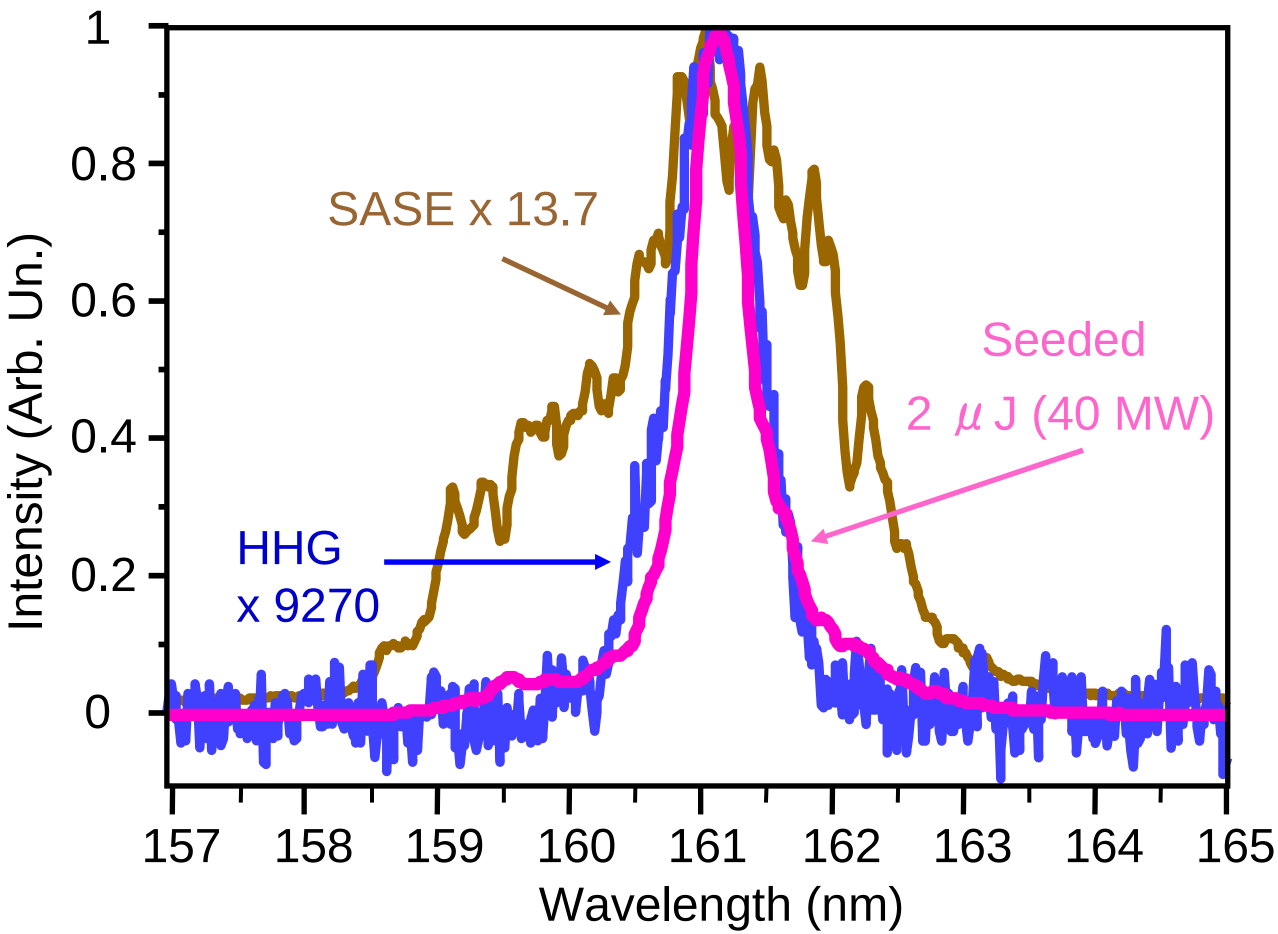
~ 100 nJ - nJ

-Limited energy per pulse
Compared to SASE shot noise?

Direct seeding with HHG at 160 nm at SCSS: fundamental spectrum

SCSS Test Accelerator (Japan) at 150 MeV with 4.5 m long undulator sections

(Lambert, Nature Physics 4, 2008)



-High amplification

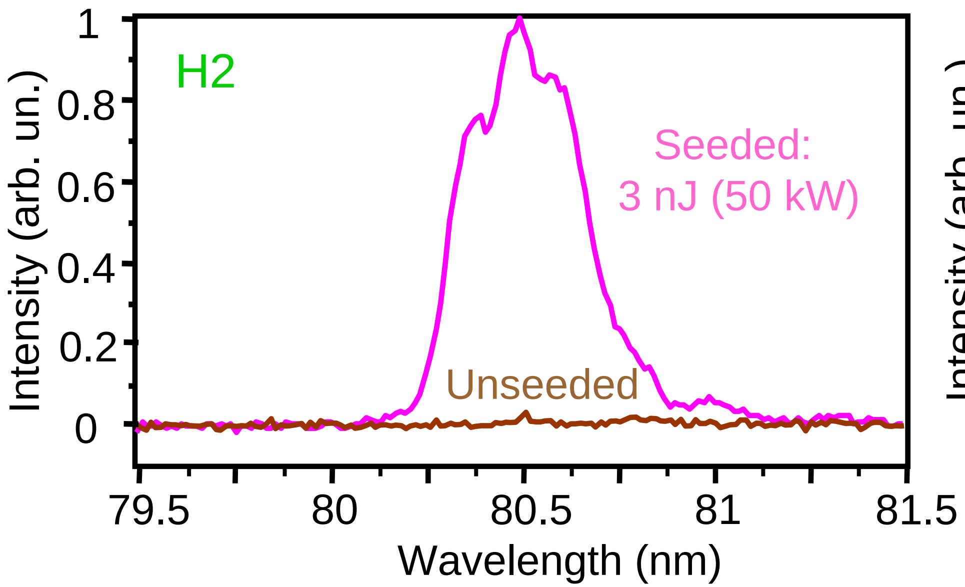
-Regular and quasi-perfect Gaussian shape

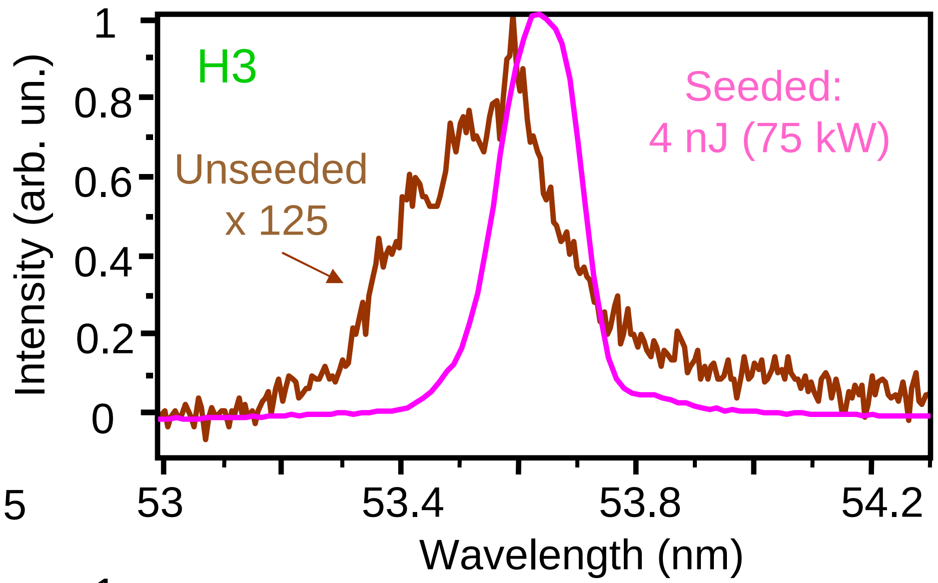
-Spectral width / ~5

-Pulse duration / ~20
Unseeded: 1 ps
HHG: 50 fs
Seeded: 50 fs

Strong improvement of the temporal coherence/SASE

Non Linear Harmonic spectra





(Tanikawa, EPL 94, 2011)

-Odd and even harmonics from 2nd (80 nm) to 7th (23 nm)

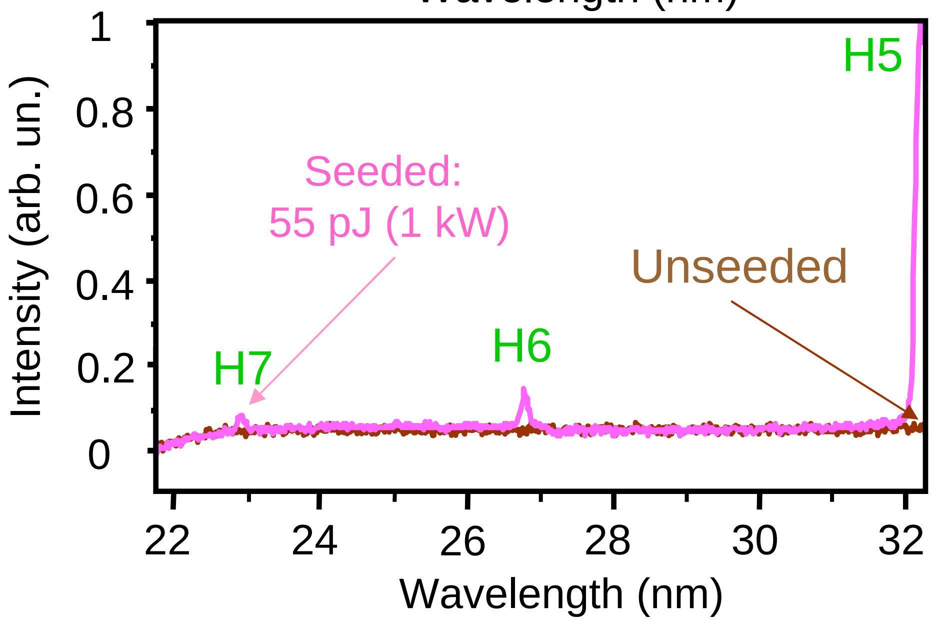
-Clear amplification

-Regular and quasi Gaussian spectral shape

-Spectral narrowing

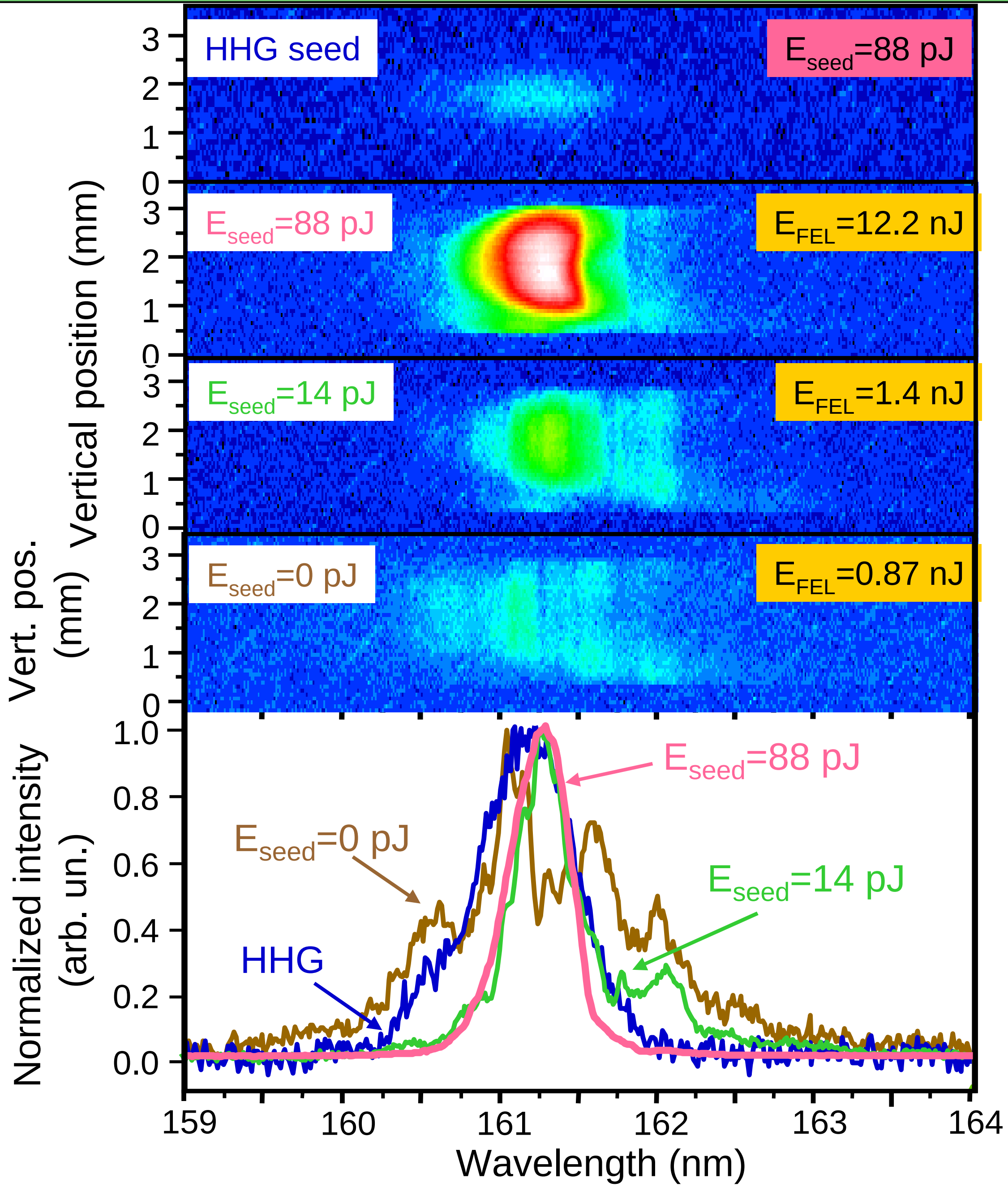
-Shorter pulse duration

Improvement of the temporal coherence



Intense and coherent emission at short wavelength while E=150 MeV

Evaluation of the seed level requirement for observing coherent emission



For $E_{seed} \geq 88$ pJ:
- Stable emission
- Regular and quasi Gaussian spectral profiles

Very weak level of injection

88 pJ (160 nm) —> 10 pJ (spatial overlapping) or ~ $200xP_{e,\text{ shot noise}}$

At 13 nm ($P_{e,\text{ shot noise}}$ <10 W) —> E_{seed} < 0.7 nJ (200x10Wx10x35fs)

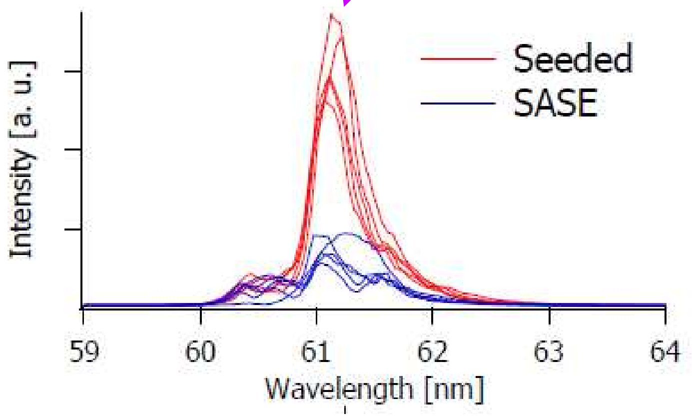
Seeding in XUV !

Below 13 nm is a challenge!

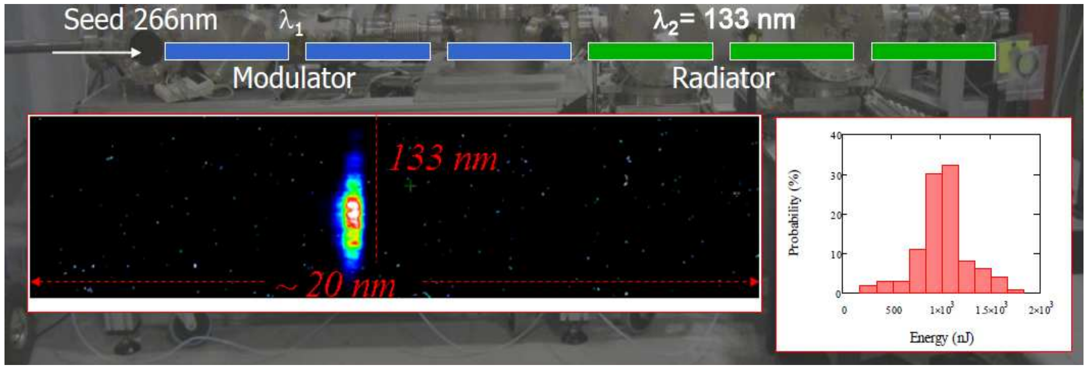
(Lambert, EPL 88, 2009)

Overview of the HHG seeded FELs

Name	*Wavelength (nm)*	*state*	*Seeding process*	*Country*
SCSS Test Accelerator	60 / 160	demonstrated	Direct HHG	Japan
SPARC	160 / 266	demonstrated	Direct HHG / HGHG	Italy
sFlash	38-13	Due 2010-2011	Direct HHG	Germany
Fermi	100-10	Due 2011-2012	HGHG, direct HHG?	Italy
SwissFEL	5	Due 2018	EEHG, direct HHG	Switzerland
SPARX	15	Due ?	HGHG, direct HHG?	Italy



(Togashi, Optics Express 19, 2011)



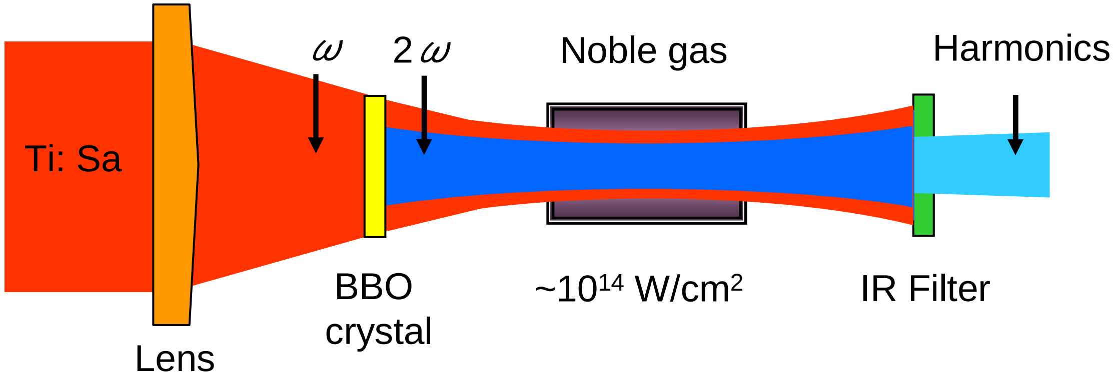
(Giannessi, Proceedings FEL10 JACOW (2011) Labat WE0B3)

What has to be improved on HHG for seeding FEL in future?

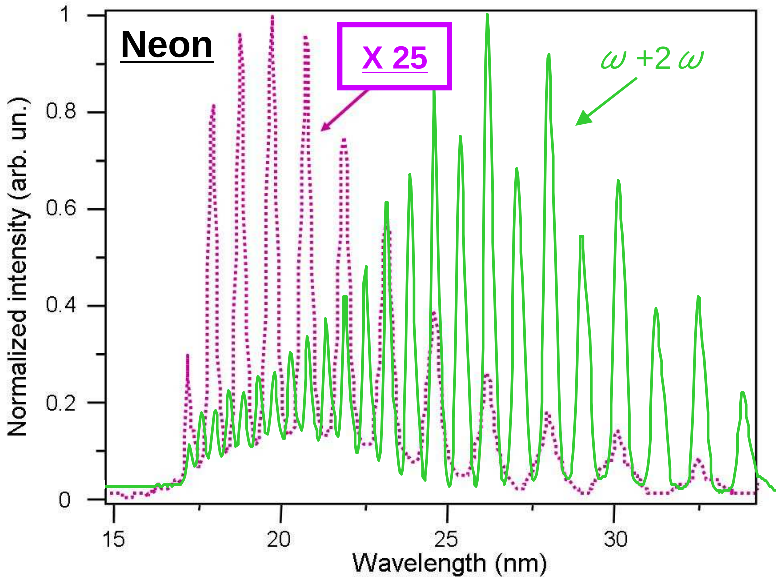
Harmonics properties relevant for seeding	
<u>Already obtained</u>	<u>To be improved</u>
-fs pulse duration -Full coherence -High repetition rate: kHz HH currently First MHz HH in xenon (J. Boullet et al. *optics letters*, 34, 1489 (2009))	-Intensity at short wavelengths -Tuneability (only odd HH): => need to considerably chirp the driving laser and/or change the gap of the undulator Two colour mixing -Wavefront: diffraction limited beam (aberration-free) => need to drastically clip the IR or HH beam or use adaptive optics for IR or HH -Variability of the polarization -Stability of the shot to shot intensity

Keep the simplicity of the classical HHG setup

Technical principle:



(Lambert, NJP 11, 2009)



-double harmonic content
even types:
2x(2n+1) from 2ω
2x(2n) from the mixing

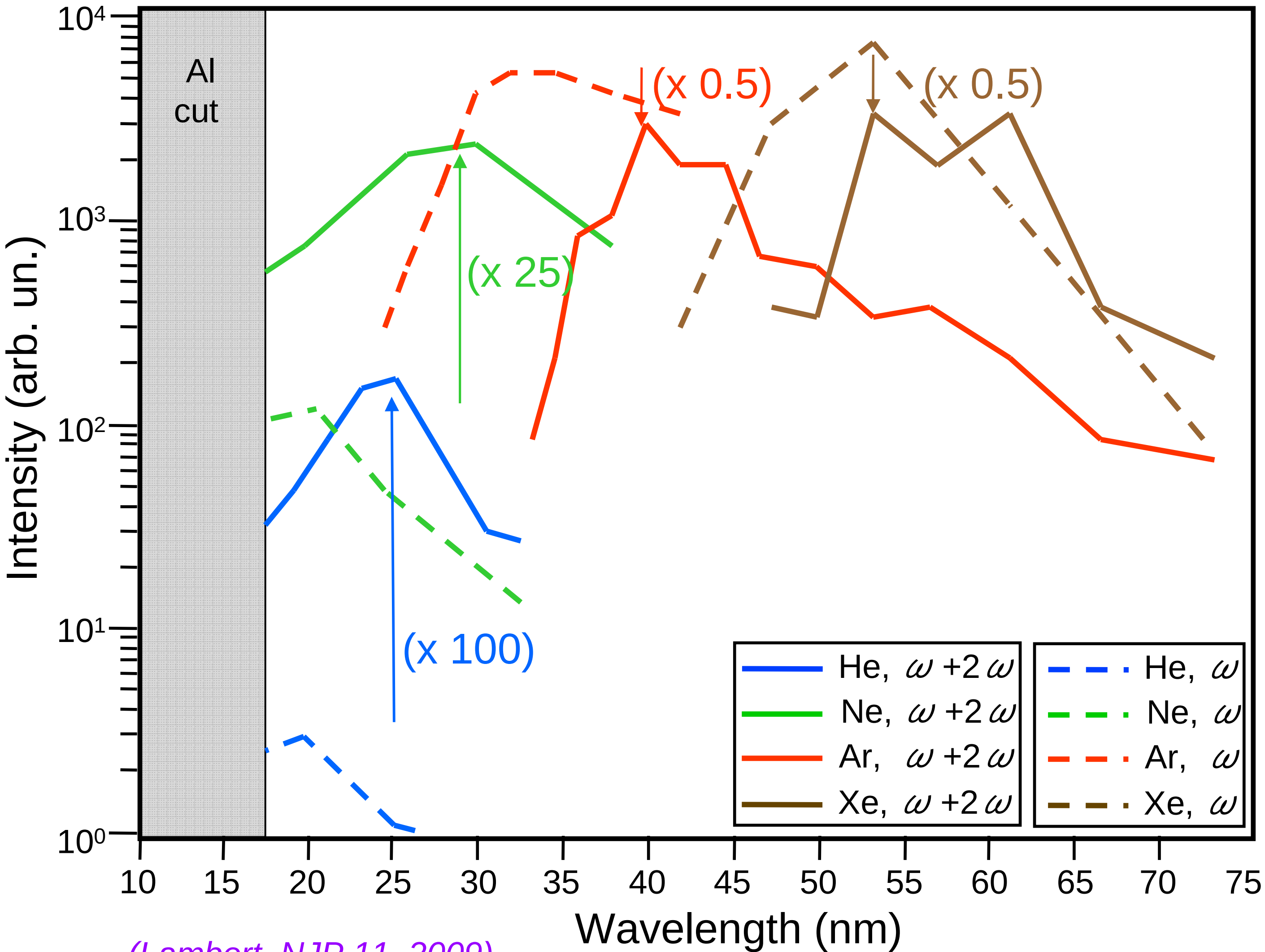
-redshift: $E_{Cut-off} = I_P + 3.2U_P$

$$U_p \propto I_{Laser}\lambda^2_{Laser}$$

-increase of the number of photons

Harmonic spectra obtained with either ω or $\omega+2\omega$ technique

100 µm thick BBO crystal, and with the optimization parameters corresponded to ω:
E_ω<6 mJ, L_C=7-9 mm and P_G=30-35 mbar



(Lambert, NJP 11, 2009)

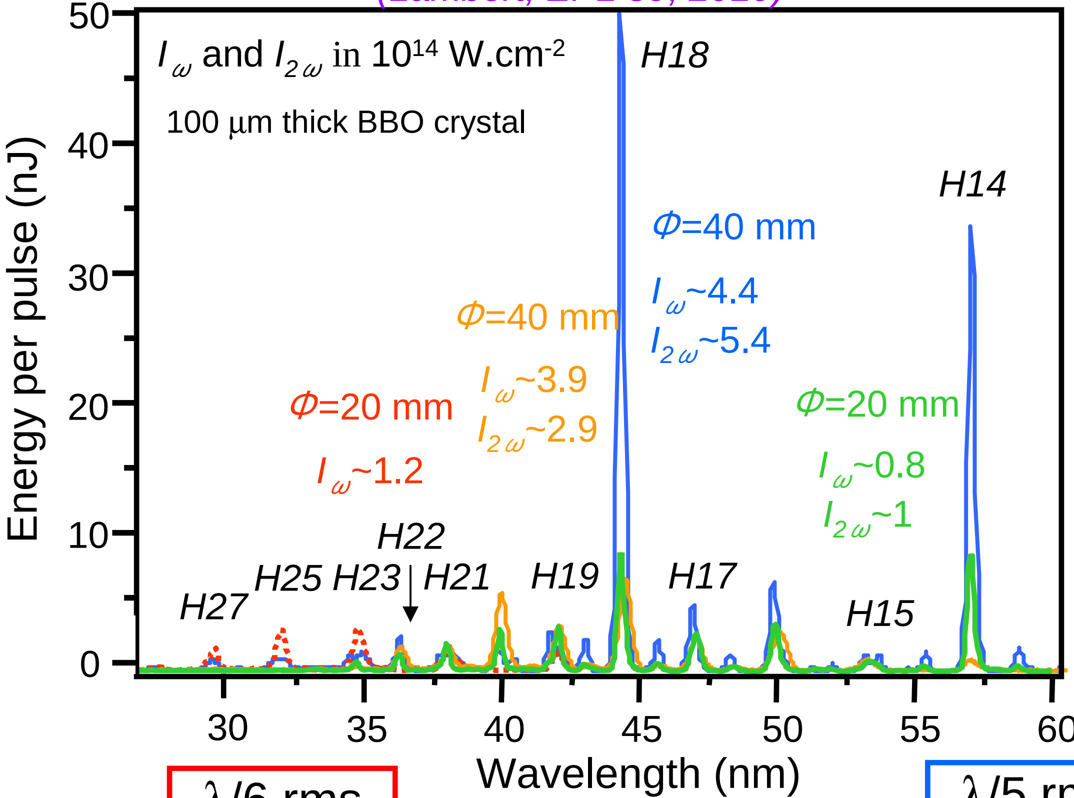
-Flat spectra (same intensity level for odd and even harmonics)

-Increase limited at high wavelengths due to an already relatively high efficiency for Xe and Ar

=> <u>$\omega+2\omega$ technique compensates the weak efficiency at short wavelengths</u>

Optimization of both flux and wavefront (Ar gas)

(Lambert, EPL 89, 2010)



-iris clipping technique:

change the focusing geometry/energy

clean the major part of the distortions in the outer part of the beam: λ to λ/6 rms

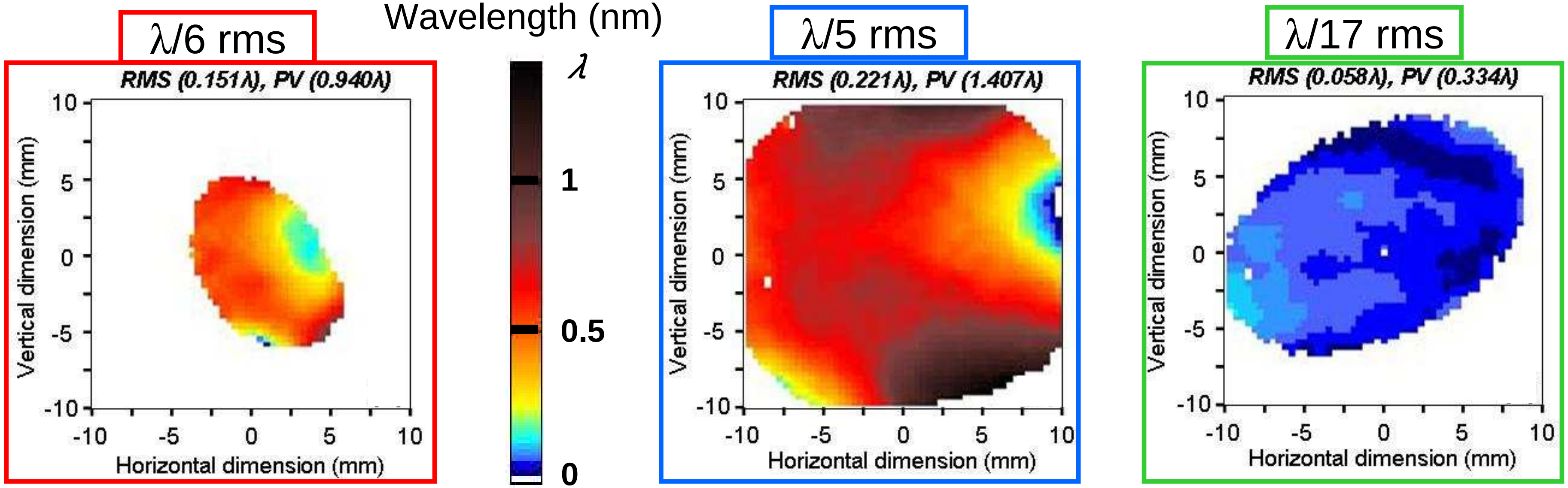
- ω (L_C=8 mm and P_G=30 mbar) to $\omega+2\omega$ (L_C=4 mm and P_G=16 mbar)

-very high increase on 2x(2n+1) type of even harmonics (50 nJ) due to strong blue/IR and distortions limited: λ/5 rms

-iris clipping: limited decrease of intensity

But distortions about λ/17 rms:

First aberration-free high harmonic beam

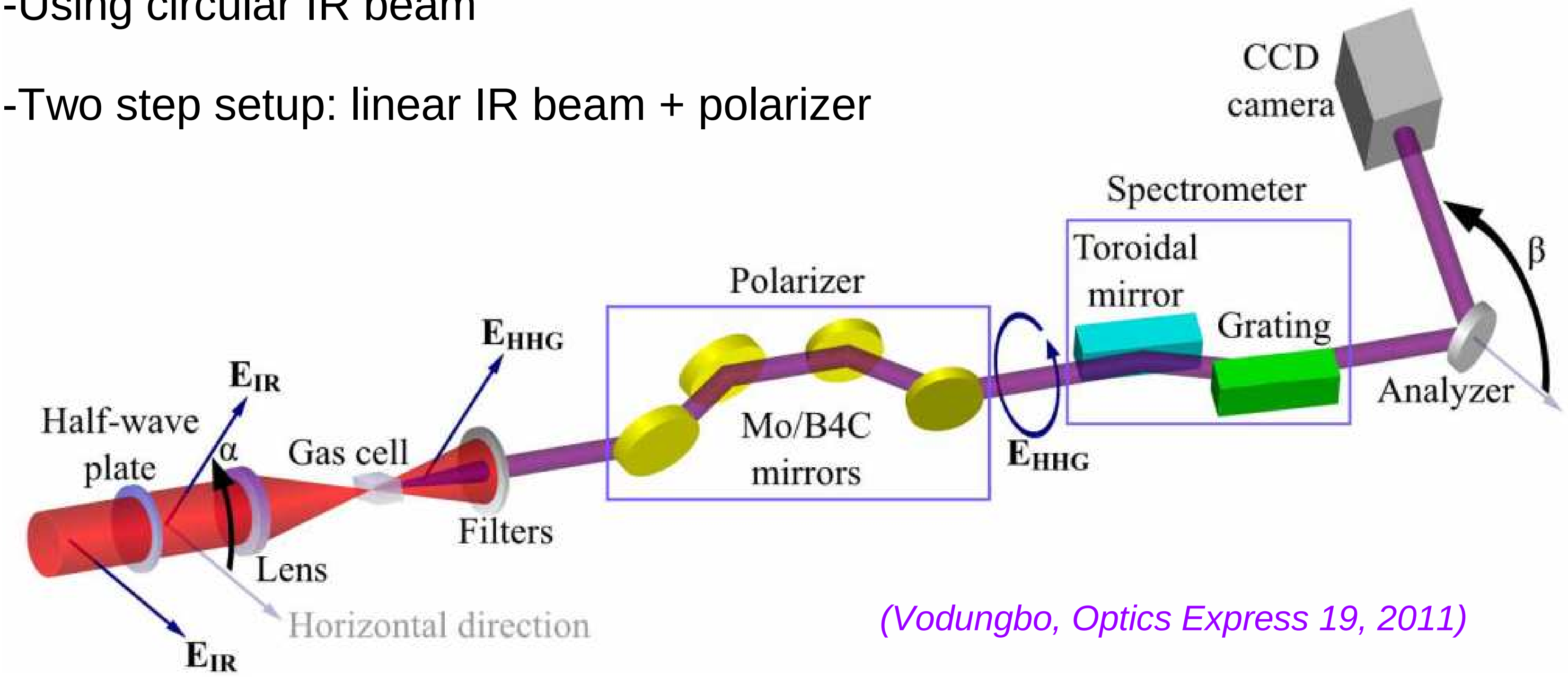


Then next?

Already obtained	To be improved
-fs pulse duration	-Variability of the polarization
-Full coherence	-Stability of the shot to shot intensity?
-High repetition rate: kHz to MHz soon	
-Intensity at short wavelengths	
-Tuneability: both odd and even harmonics	
Use parametric amplifier (1.2-1.5 µm)	
-Wavefront: aberration-free beam	
-Simple system	

-Using circular IR beam

-Two step setup: linear IR beam + polarizer

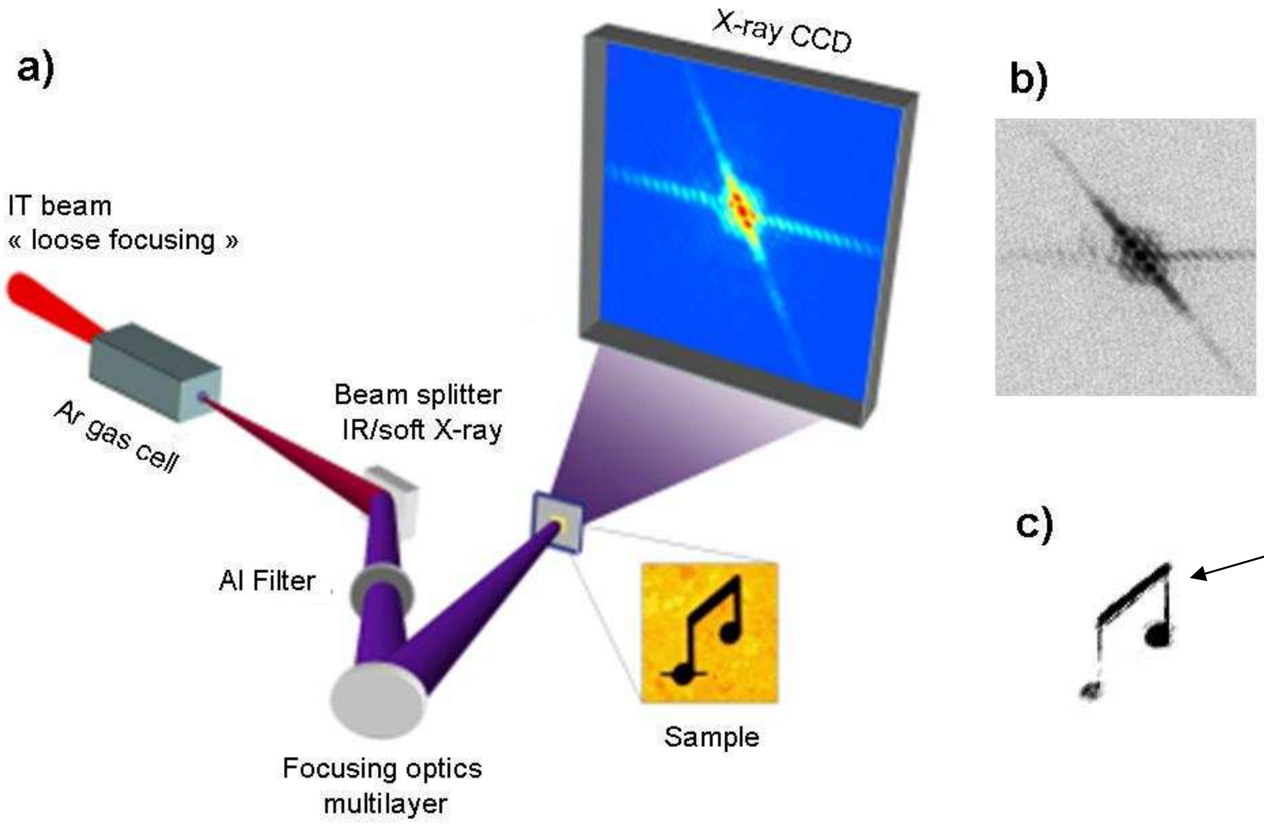


(Vodungbo, Optics Express 19, 2011)

Harmonic order	31^{st}	33^{rd}	35^{th}	37^{th}	39^{th}	41^{st}	43^{rd}	45^{th}
λ (nm)	26.3	24.7	23.3	22	20.9	19.9	19	18.1
P_{Cmax} (%)	100	100	97	91	85	76	66	61
T_C (%)	2.6	2.7	3.7	3.6	4.4	4.3	4.0	3.7

In XUV performances are close: weak flux harmonics
weak temporal coherence

Single shot coherent diffraction imaging of nano-object *(Ravasio et al. PRL 103 (2009)*

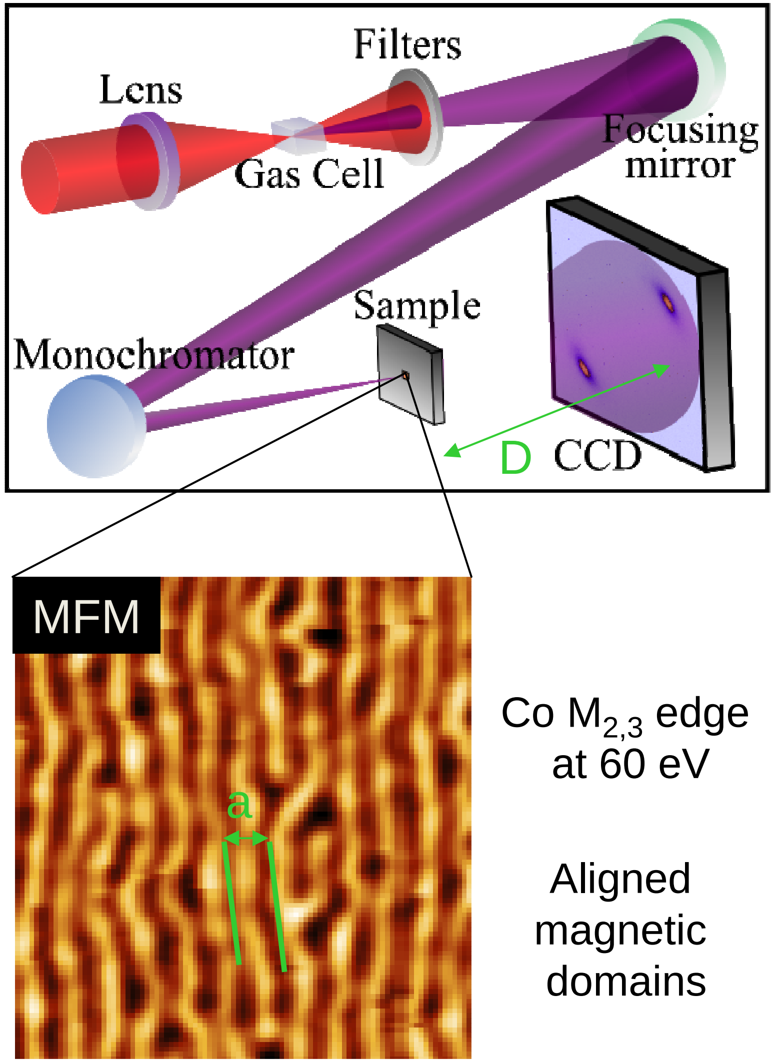


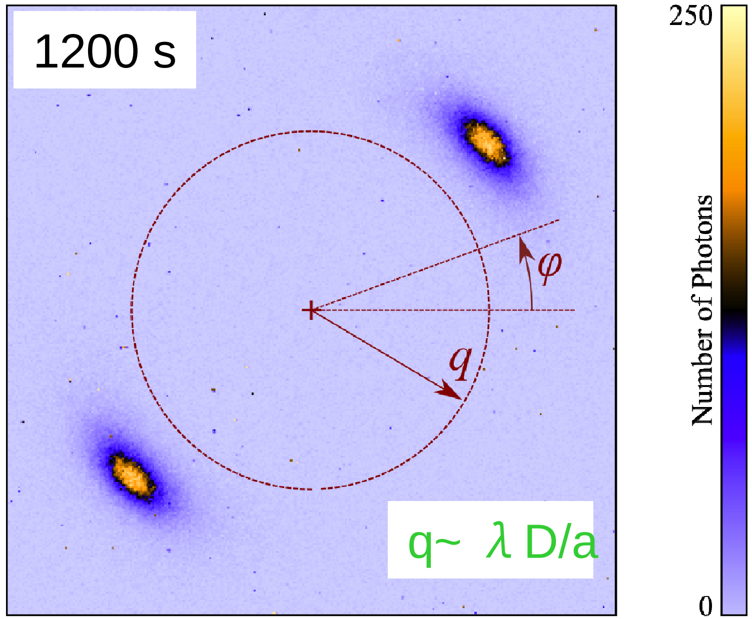
32 nm, 1 μ J, 20 fs

Reconstructed image with 119 nm resolution

Natural synchronization between Laser and HH

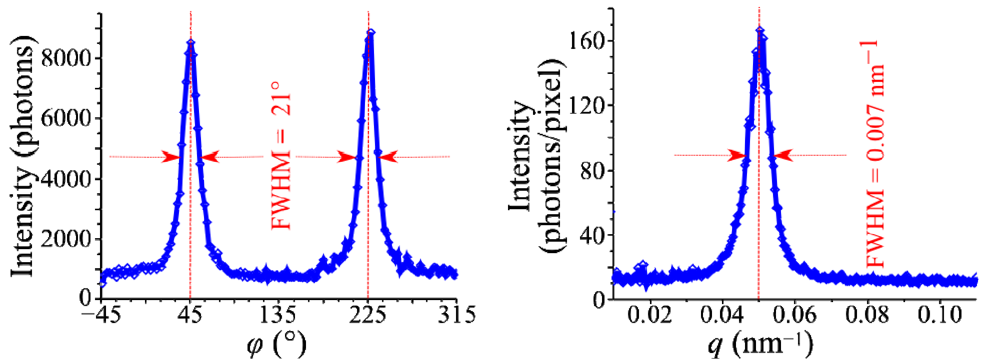
Coherent diffraction imaging of magnetic domains *(Vodungbo, EPL 94, 2011)* :



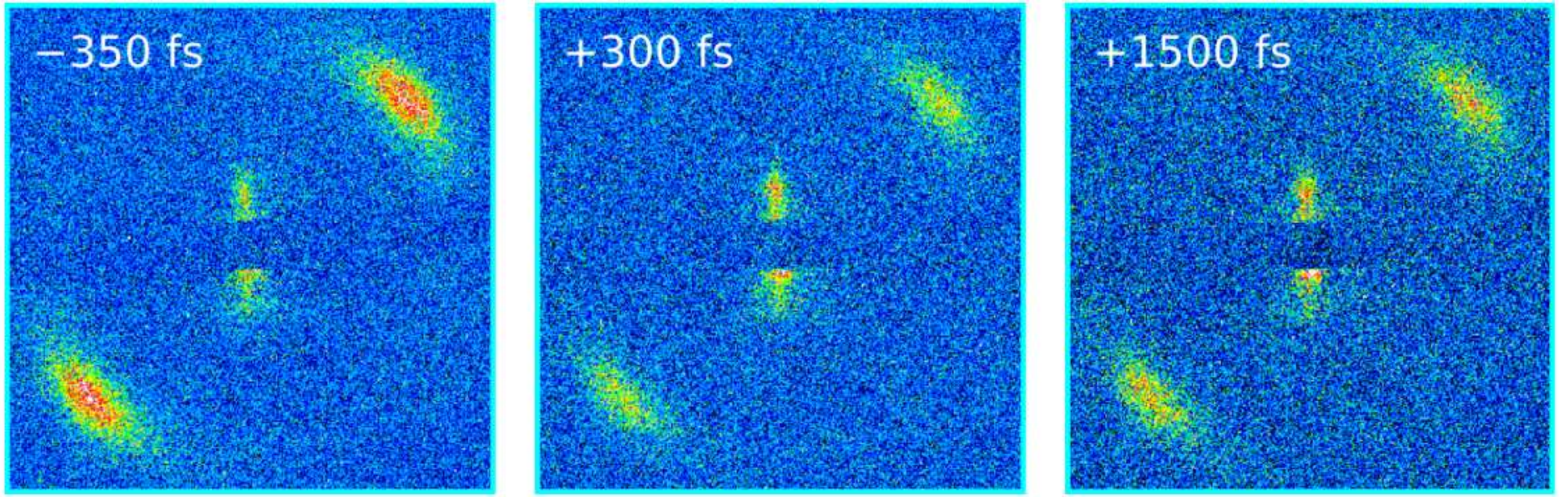


Co $M_{2,3}$ edge
at 60 eV

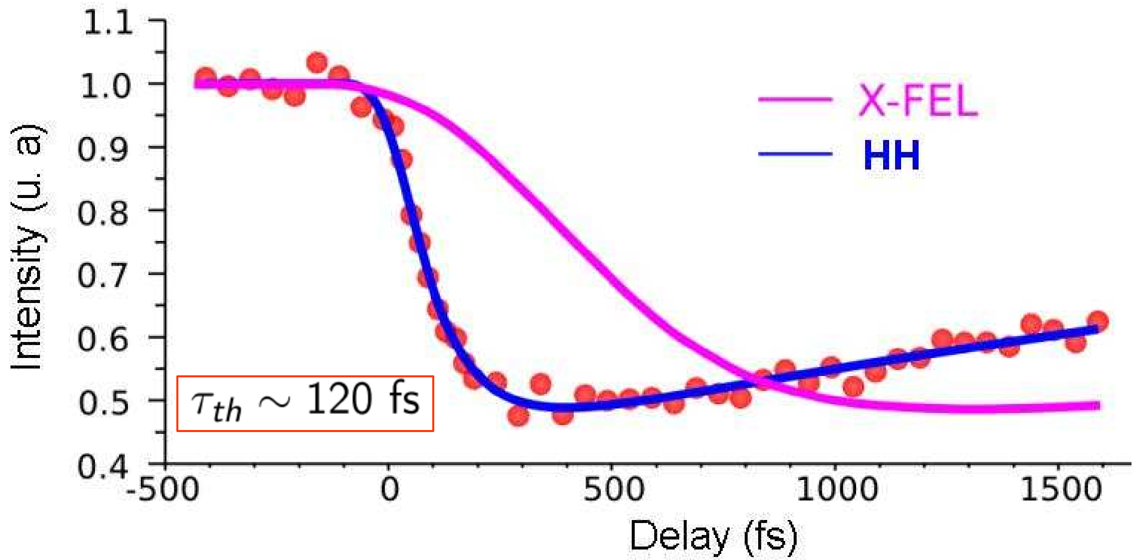
Aligned
magnetic
domains



-Magnetic domain orientation: 45° +- 10°
-Width distribution of magnetic domains: 65 nm +- 5 nm



Integrated density gives magnetization : I ~ M^2



-much shorter time scale
-better temporal resolution for HH?
And/or due to XFEL at 800 eV (L edge)

fitted with $G(t) * \left\{ C_0 + C_1 H(t) \left[1 - \exp\left(\frac{-t}{\tau_{th}}\right) \right] \exp\left(\frac{-t}{\tau_{s-p}}\right) \right\}$ *(Boeglin, Nature 465, 2010)*

Thank you

for your attention