Harmonic lasing in X-ray FELs: theory and experiment

E. Schneidmiller, B. Faatz, M. Kuhlmann, J. Rönsch-Schulenburg,
S. Schreiber, M. Tischer, M. Yurkov

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Outline

- Harmonic lasing
- Harmonic lasing self-seeded (HLSS) FEL
- Experiments at FLASH

Harmonics in FELs

- In a planar undulator (K ~ 1 or K >1) the odd harmonics can be radiated on-axis (widely used in SR sources)

- For coherent emission a mechanism is required to create coherent microbunching at harmonic frequencies

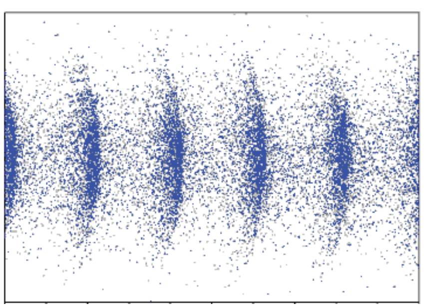
- There are two basic mechanisms in FELs:
  - Nonlinear harmonic generation
  - Harmonic lasing

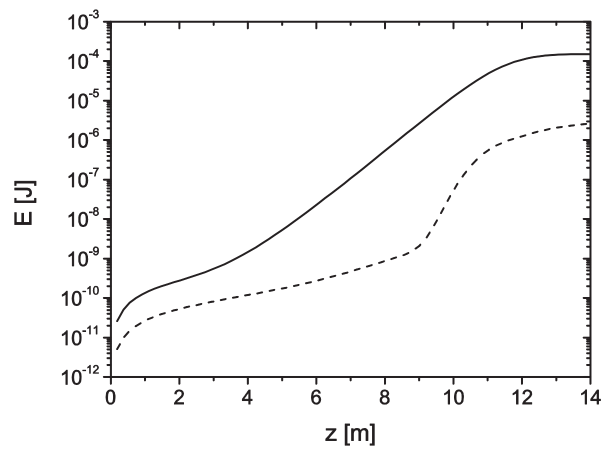
We consider SASE process in a baseline XFEL undulator

Nonlinear harmonic generation

- When lasing at the fundamental frequency approaches saturation, the density modulation becomes nonlinear (contains higher harmonics)
- Odd harmonics are radiated then on-axis
- Well-known process, studied in many papers

Microbunching at saturation





1st: solid

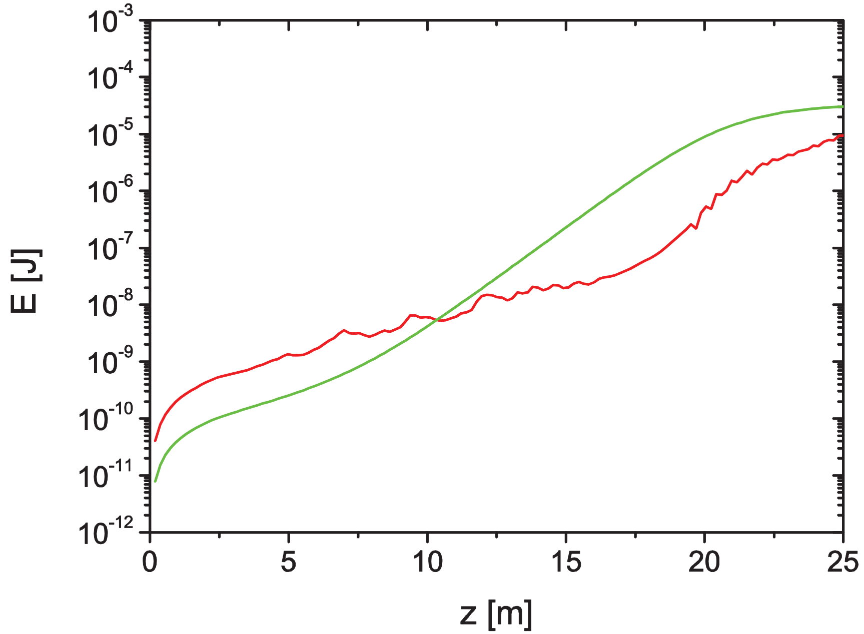
3rd: dash

3rd harmonic is driven by the fundamental

Occurs whenever an FEL reaches saturation; studied and used at FLASH, LCLS etc.

Harmonic lasing

- Harmonic lasing is an FEL instability developing independently of the fundamental (in linear regime)
- We have to disrupt the fundamental to let a harmonic saturate



1st: red
3rd: green

the fundamental is disrupted by phase shifters

Properties of harmonic lasing

- Saturation efficiency of h-th harmonic scales as ~ $\lambda_w/(hL_{sat})$
- Relative rms bandwidth scales as ~ $\lambda_w/(hL_{sat})$
- Shot-to-shot intensity fluctuations are comparable (the same statistics)
- Good transverse coherence

Brilliance is comparable to that of the fundamental!

Harmonic lasing: the history

- First theoretical consideration for low-gain FELs more than 30 years ago (Colson, 1981)
- Several successful experiments with FEL oscillators in infrared range (1988-2010)

- High-gain FELs:

1D theory of harmonic lasing:

Murphy, Pellegrini, Bonifacio, 1985
Bonifacio, De Salvo, Pierini, 1990
McNeil et al., 2005

3D theory (everything included):

Z. Huang and K.-J. Kim, 2000

Our findings in 2012

- Found simple parametrization of the gain length and upgraded FEL code FAST
- Could then analyze parameter space (with optimistic conclusions)
- Proposed new methods for suppression of the fundamental
- Discovered qualitatively new effect of anomalously strong harmonic lasing for thin electron beams
- Suggested method for improvement of spectral brightness (later called HLSS FEL)
- Considered practical applications to different facilities

Our conclusion: the option should be seriously considered!

E. Schneidmiller and M. Yurkov, Phys. Rev. ST-AB 15(2012)080702

Harmonics vs the retuned fundamental

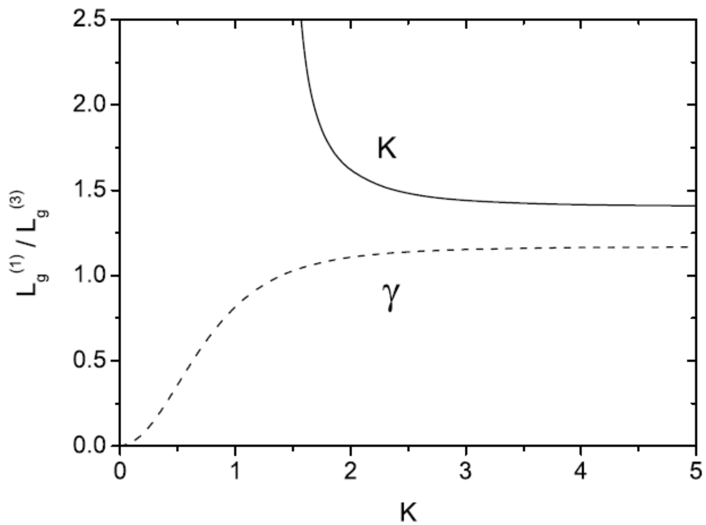
A. Harmonic lasing (with the suppressed fundamental) at some WL vs fundamental lasing at the same WL with reduced K.

$$\frac{L_g^{(1K)}}{L_g^{(h)}} = \frac{h^{1/2} K A_{JJh}(K)}{K_{re} A_{JJ1}(K_{re})} \qquad K_{re}^2 = \frac{1+K^2}{h} - 1$$

B. Harmonic lasing (with the suppressed fundamental) at some WL vs fundamental lasing at the same WL with increased beam energy.

$$\frac{L_g^{(1\gamma)}}{L_g^{(h)}} = \frac{h^{5/6} A_{JJh}(K)}{A_{JJ1}(K)}$$

Negligible energy spread, beta is optimized in all cases



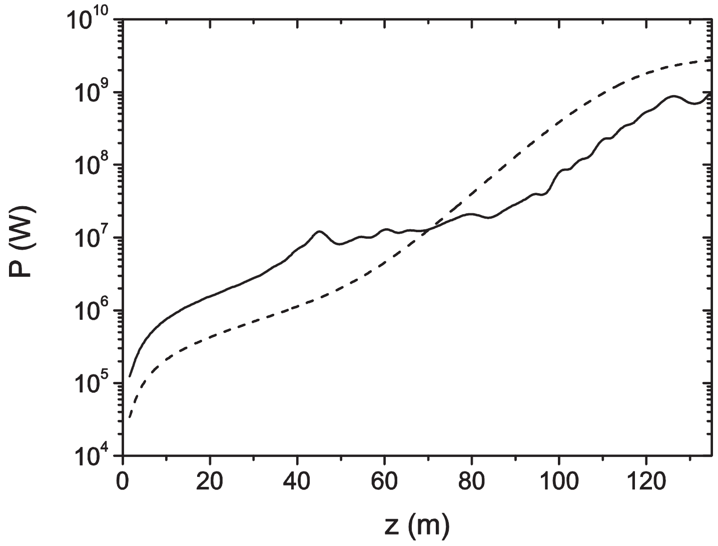
Better than in 1D!

Suppression of the fundamental

- Phase shifters
- Spectral filtering
- Switching between 3rd and 5th harmonics

Example for the European FEL

3rd harmonic lasing at 62 keV (0.2 A). Beam parameters for 100 pC from s2e (quantum diffusion in the undulator added), energy 17.5 GeV. With 20 pC bunch one can even reach 100 keV.



1st: solid

3rd: dash

bandwidth is 2×10^{-4} (FWHM)

Users are interested; MAC recommended.

CW upgrade of the European XFEL

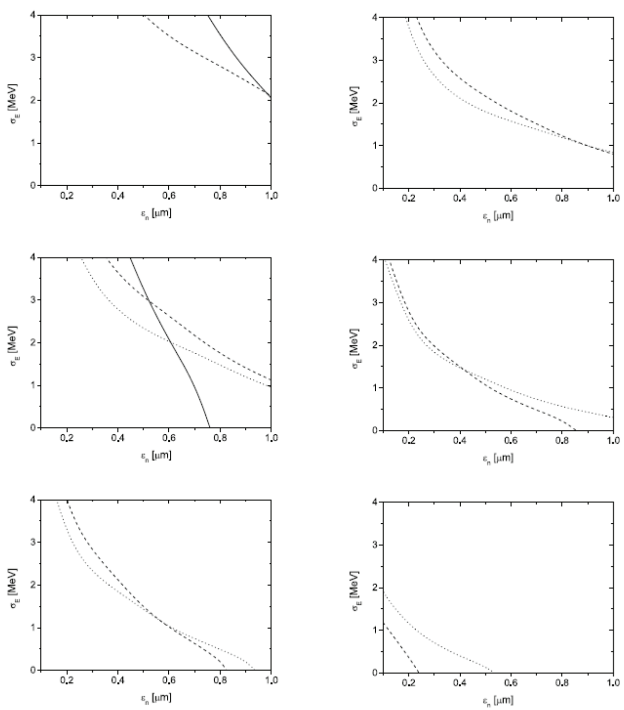
It is expected to have 7 GeV in CW mode and 10 GeV in long pulse mode with 35% duty factor.

10 GeV | 7 GeV

1 A

0.75 A

0.5 A



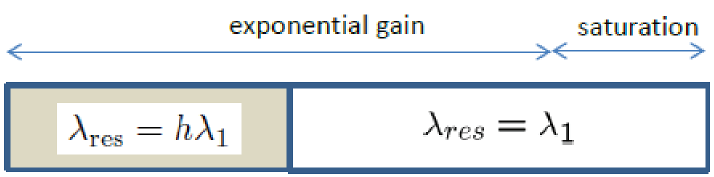
1[st]: solid
3[rd]: dash
5[th]: dot

Brinkmann, Schneidmiller, Sekutowicz, Yurkov, NIMA 768(2014)20

HLSS FEL (Harmonic Lasing Self-Seeded FEL)

We proposed a simple trick for improvement of spectral brightness in a gap-tunable undulator: harmonic lasing in linear regime (with narrow bandwidth) in the first part of the undulator, then reducing K and reaching saturation at the fundamental. Then we have high power and narrow BW.

E. Schneidmiller and M. Yurkov, Phys. Rev. ST-AB 15(2012)080702



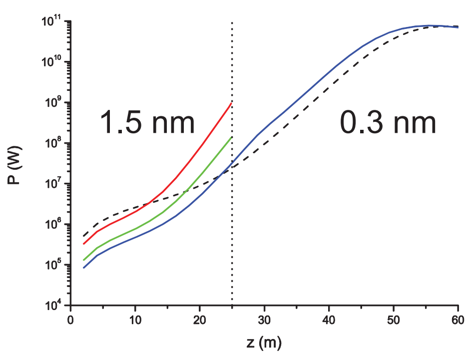
larger K   smaller K

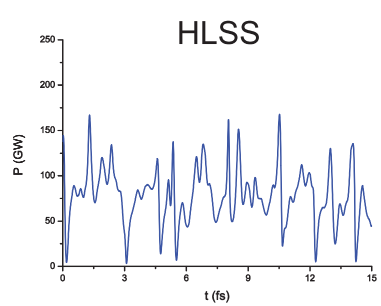
Bandwidth reduction factor:

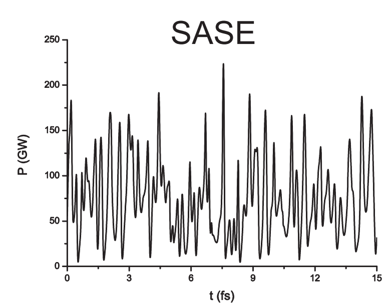
$$R \simeq h\,\frac{\sqrt{L_{\rm w}^{(1)} L_{{\rm sat},h}}}{L_{{\rm sat},1}}$$

Typically R = 0.6-0.9 h

The fundamental and all harmonics have to stay well below saturation in the first part of the undulator. Use of phase shifters in the first undulator is optional.







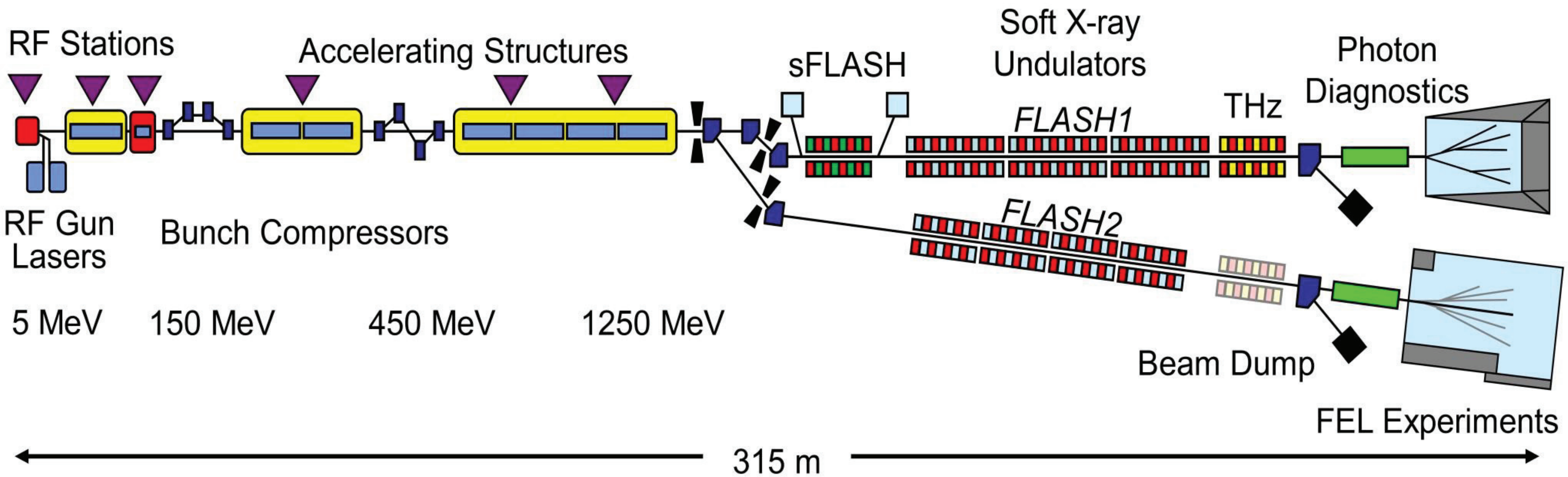
E. Schneidmiller and M. Yurkov, FEL'13

HLSS and post-saturation taper

- Post-saturation taper works better for seeded FELs;
- Coherence length does not have to equal bunch length, even moderate increase is sufficient;
- In self-seeding schemes the saturation length is about twice that of SASE: less space for post-saturation taper;
- HLSS saturates even earlier than SASE: more space for post-saturation taper, more power can be extracted.

HLSS FEL seems to be the optimal solution for maximizing FEL power.

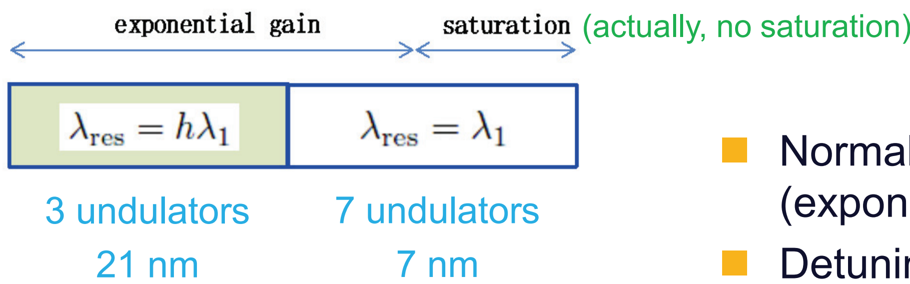
FLASH layout



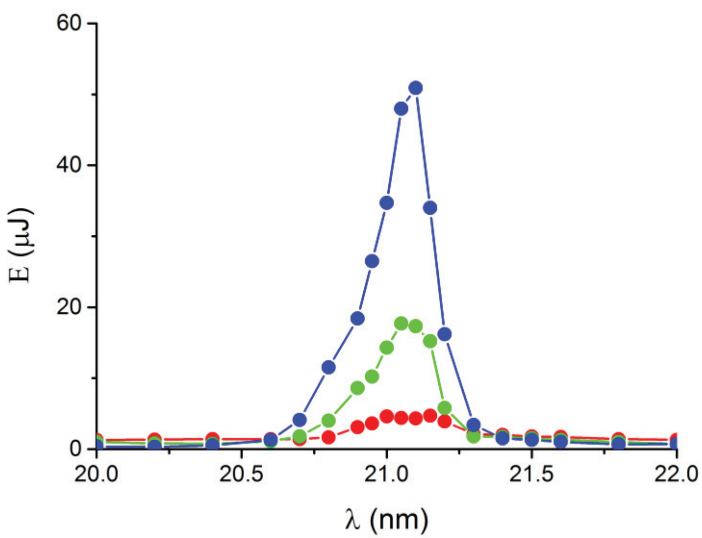
- Undulators

	Period	Length	
FLASH1:	2.73 cm	27 m (6 x 4.5 m modules)	fixed gap
FLASH2:	3.14 cm	30 m (12 x 2.5 m modules)	variable gap

HLSS at FLASH2: 7 nm (May 1, 2016)



K-scan of the undulators: only 1st (red); 1st and 2nd (green) ; 1st, 2nd and 3rd (blue)



- Normal SASE at 7 nm in 10 undulators: 12 uJ (exponential gain)
- Detuning first (first two, first three) undulator sections: sharp intensity drop
- Coming close to 21 nm: sharp increase, resonant behavior
- With 3 undulators we have 51 uJ instead of 12 uJ; gain length of the 3rd harmonic is shorter than that of the fundamental at 7 nm!
- Nonlinear harmonic generation in the first part is absolutely excluded: pulse energy at 21 nm after 3 undulators was 40 nJ (but about 200 uJ at saturation): 4 orders of magnitude
- Results can only be explained by 3rd harmonic lasing at 7 nm

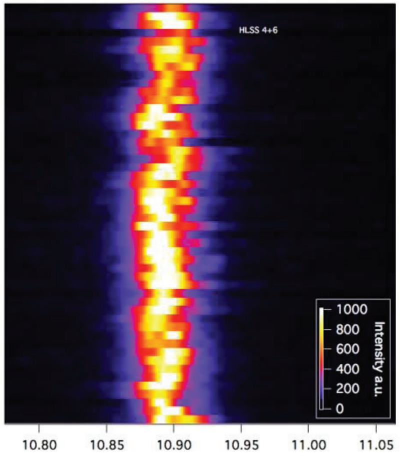
E. Schneidmiller et al., Phys. Rev. ST-AB 20(2017)020705

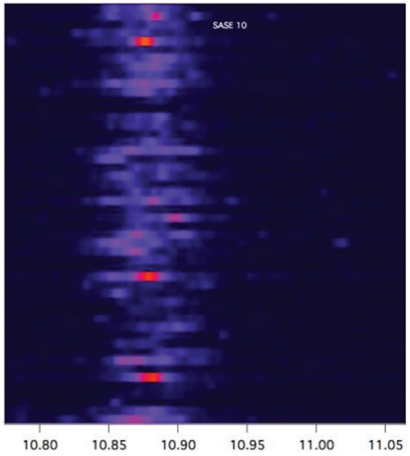
HLSS at FLASH2: 11 nm (June 6-7, 2016)

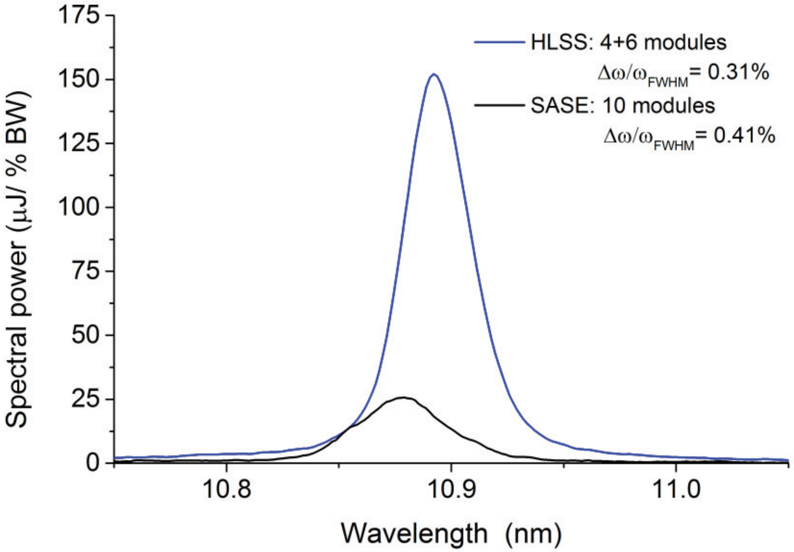
Spectral measurements

HLSS (4+6)

SASE (10)







Expectations

$$R \simeq h\,\frac{\sqrt{L_{\rm w}^{(1)} L_{{\rm sat},h}}}{L_{{\rm sat},1}}$$

R = 1.7

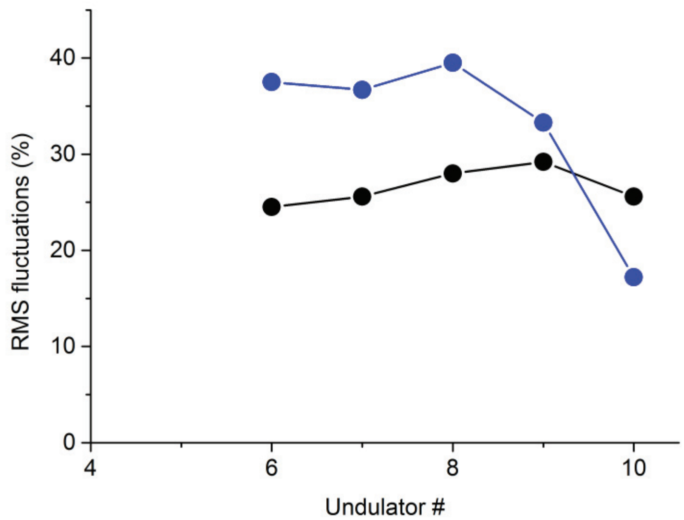
Measured: R = 1.3

Energy chirp!

E. Schneidmiller et al., Phys. Rev. ST-AB 20(2017)020705

c. HLSS at FLASH2: 11 nm (June 6-7, 2016)

Statistical determination of an increase of the coherence time



SASE (black) and HLSS (blue)

$$M_l \propto 1/L^{coh}$$

$$M_l = 1/\sigma^2$$

$$\frac{L^{coh}_{HLSS}}{L^{coh}_{SASE}} = \frac{\sigma^2_{HLSS}}{\sigma^2_{SASE}} \simeq 1.8$$

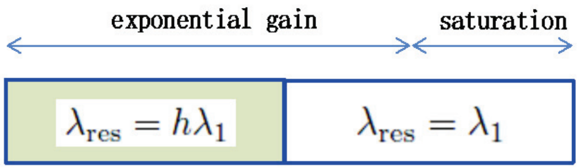
Expectations

$$R \simeq h \, \frac{\sqrt{L_{\mathrm{w}}^{(1)} L_{\mathrm{sat},h}}}{L_{\mathrm{sat},1}}$$

R = 1.7

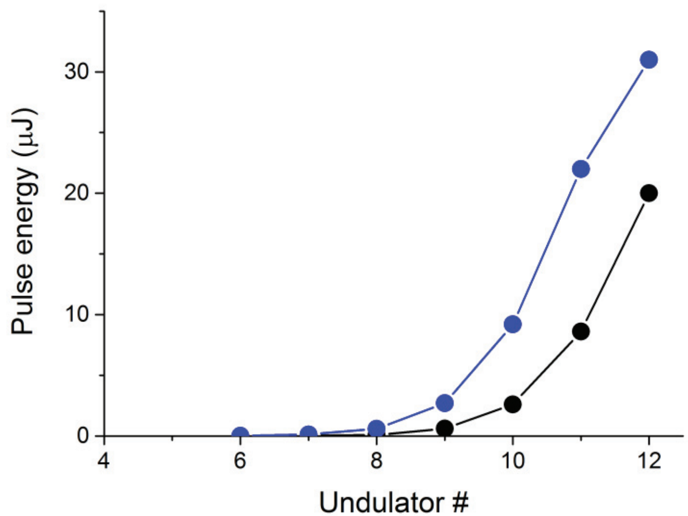
E. Schneidmiller et al., Phys. Rev. ST-AB 20(2017)020705

HLSS at FLASH2: 15 nm (Nov. 11, 2016)



4 undulators 45 nm

8 undulators 15 nm

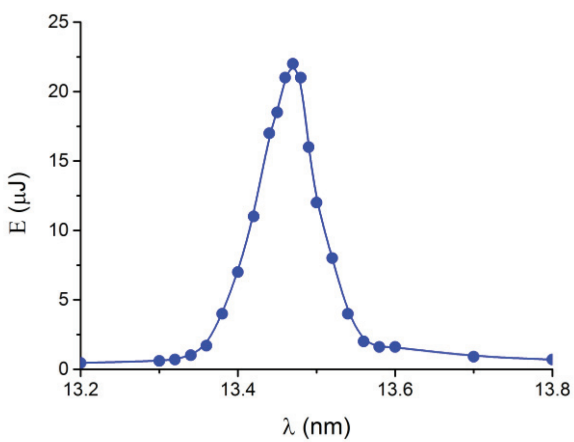


Post-saturation taper is applied:
SASE (black) and HLSS (blue)

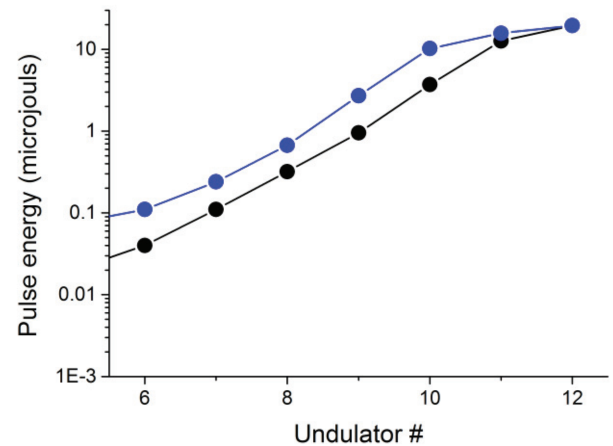
E. Schneidmiller et al., Phys. Rev. ST-AB 20(2017)020705

HLSS at FLASH2: 4.5 nm (Sep. 18, 2016)

exponential gain	saturation
$\lambda_{\rm res} = h\lambda_1$	$\lambda_{\rm res} = \lambda_1$
3 undulators	9 undulators
13.5 nm	4.5 nm



K-scan of the first 3 undulators



Gain curve: SASE (black) and HLSS (blue)

E. Schneidmiller et al., Phys. Rev. ST-AB 20(2017)020705

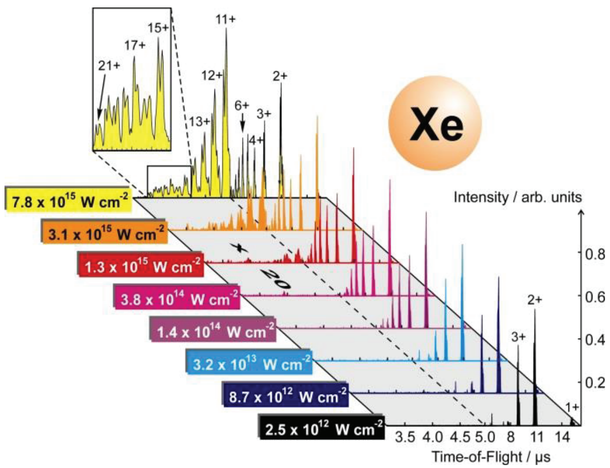
HLSS at PAL XFEL (2017)

- Soft X-ray undulator was used to test HLSS;
- It worked very well at 1 nm;
- Good agreement with theory.

HLSS for FLASH users (last week)

Proposal: Influence of the coherence of FEL radiation on the multiphoton ionization of highly correlated quantum systems

K. Tiedtke, A.A. Sorokin, M. Richter et al.



A. A. Sorokin, S. V. Bobashev, T. Feigl, K. Tiedtke, H. Wabnitz, and M. Richter, *Photoelectric effect at ultra-high intensities,* Phys. Rev. Lett. **99**, 213002 (2007

- Use SASE and HLSS;
- Keep the same pulse energy, pulse duration, source position etc. but change coherence time;
- First results are exciting!

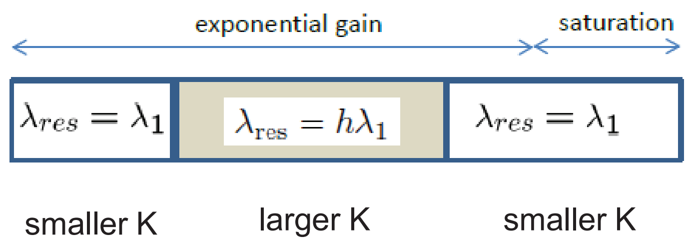
Conclusions

- Harmonic lasing is an interesting option for XFELs;
- Main application I: extension of photon energy range;
- Main application II: bandwidth reduction and brilliance increase (HLSS);
- Successful demonstration of HLSS principle at FLASH2;
- First evidence of harmonic lasing in a high-gain FEL and at a short wavelength (4.5 nm) paves the way for its applications in X-ray FEL facilities.
- HLSS at PAL XFEL: reached 1 nm
- First successful user experiment at FLASH

Backup slides

HLSS vs pSASE

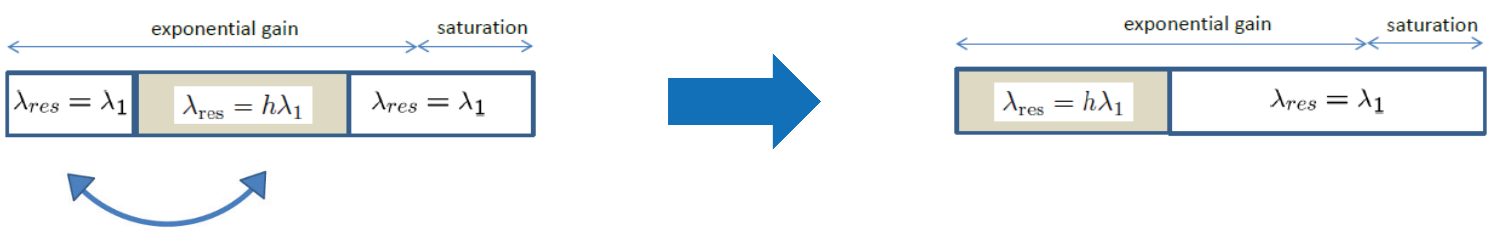
A similar concept (pSASE): D. Xiang et al., PRST-AB 16(2013)010703



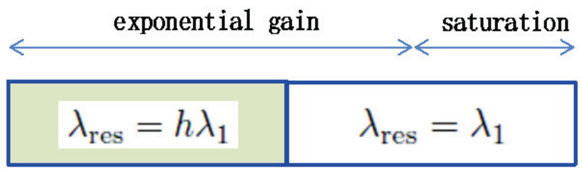
First two sections are linear amplifiers (with large BW and small BW). One can swap them and keep the same properties of radiation in the end (small BW and high power):

pSASE FEL

HLSS FEL



HLSS at FLASH2: simulations



No tapering (log scale)

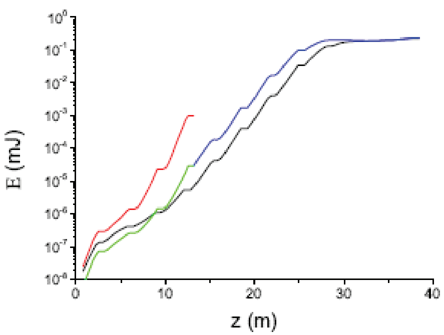


Figure 2: FEL pulse energy versus undulator length. In the first part of the undulator (tuned to the resonance with 39 nm) the first (red) and the third (green) harmonics are shown. The third harmonic continues to get amplified in the second part of the undulator (now as the fundamental) tuned to 13 nm (shown in blue). A reference case of lasing at 13 nm on the fundamental in the whole undulator with constant K-value is shown in black.

Tapering (linear scale)

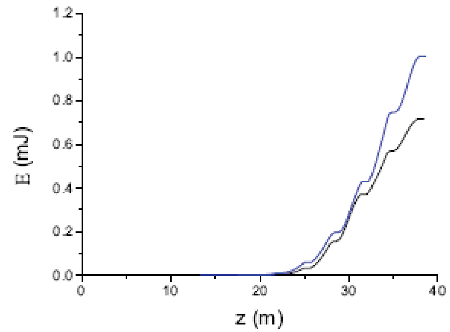


Figure 3: FEL pulse energy versus undulator length when the post-saturation taper is applied. HLSS case is shown in blue, and the SASE case - in black.

Spectral density

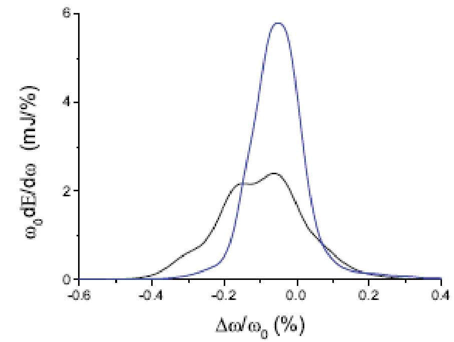


Figure 4: Spectral density of the radiation energy for HLSS FEL configuration (blue) and for SASE FEL (black).

$$R \simeq h \frac{\sqrt{L_{\mathrm{w}}^{(1)} L_{\mathrm{sat},h}}}{L_{\mathrm{sat},1}}$$

R = 0.6 h = 1.8

E. Schneidmiller and M. Yurkov, Proc. IPAC2016, MOPOW009

Gain length of harmonic lasing

Generalization of formulas from Saldin, Schneidmiller and Yurkov, Opt. Commun. 235(2004)415

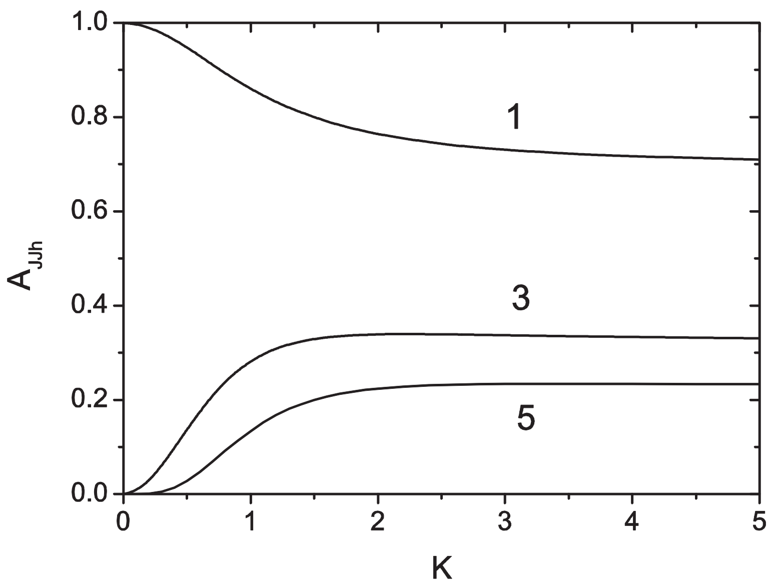
$$L_g \simeq L_{g0}\,(1+\delta)$$ field gain length

$$A_{JJh}(K) = J_{(h-1)/2}\left(\frac{hK^2}{2(1+K^2)}\right) - J_{(h+1)/2}\left(\frac{hK^2}{2(1+K^2)}\right)$$

$$L_{g0} = 1.67\left(\frac{I_A}{I}\right)^{1/2} \frac{(\epsilon_n \lambda_{\mathrm{w}})^{5/6}}{\lambda_h^{2/3}} \frac{(1+K^2)^{1/3}}{h^{5/6} K A_{JJh}}$$

$$\delta = 131\,\frac{I_A}{I}\,\frac{\epsilon_n^{5/4}}{\lambda_h^{1/8}\lambda_{\mathrm{w}}^{9/8}}\,\frac{h^{9/8}\sigma_\gamma^2}{(K A_{JJh})^2(1+K^2)^{1/8}}$$

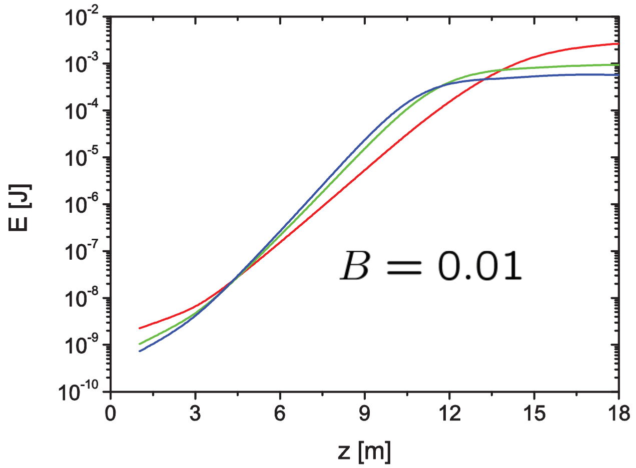
$$\beta_{\mathrm{opt}} \simeq 11.2\left(\frac{I_A}{I}\right)^{1/2} \frac{\epsilon_n^{3/2}\lambda_{\mathrm{w}}^{1/2}}{\lambda_h h^{1/2} K A_{JJh}}\,(1+8\delta)^{-1/3}$$



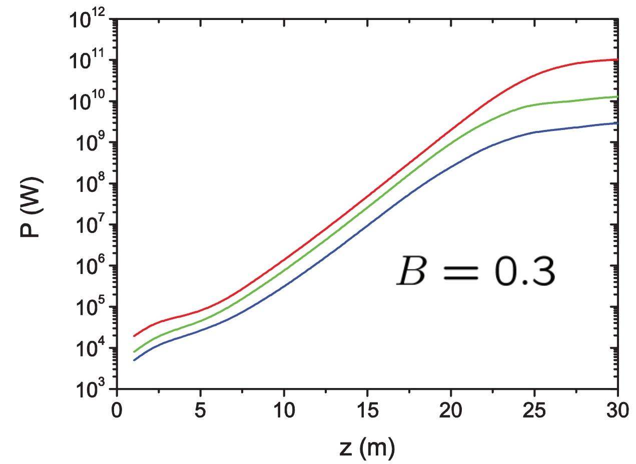
$$L_g(\beta) \simeq L_g(\beta_{\mathrm{opt}})\left[1 + \frac{(\beta-\beta_{\mathrm{opt}})^2(1+8\delta)}{4\beta_{\mathrm{opt}}^2}\right]^{1/6}$$ for $\beta > \beta_{\mathrm{opt}}$ new also for the fundamental

$2\pi\epsilon/\lambda$ ~ 1 or $2\pi\epsilon/\lambda$ >> 1

Anomalous harmonic lasing



1st: red
3rd: green
5th: blue



XFEL.EU: fundamental at 4.5 nm, beam energy 10.5 GeV, slice parameters for 100 pC from s2e, energy spread is 1 MeV

One can use this effect (in pump-probe experiments or for multi-user operation) or find ways to suppress it (if disturbs).

Anomalous harmonic lasing of a thin beam

The case $2\pi\epsilon/\lambda$ ~ 1 is typical for hard X-ray beamlines

If the same beam is used to drive a soft X-ray undulator (like SASE3 of XFEL.EU), the case $2\pi\epsilon/\lambda$ << 1 is automatically achieved

For a reasonable beta-function one deals then with a small diffraction parameter $B = 4\pi\epsilon\beta\Gamma/\lambda$ ($L_g \propto 1/\Gamma$)

If the diffraction parameter is sufficiently small and K is sufficiently large, harmonics can grow faster than the fundamental!

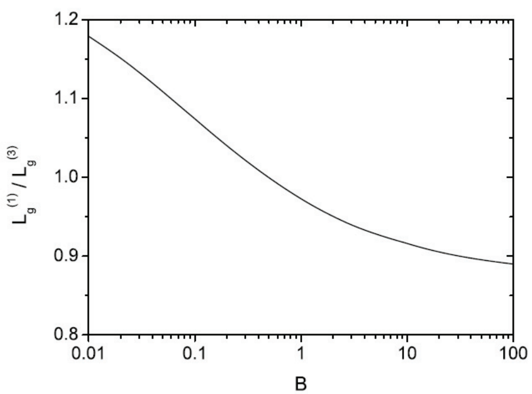
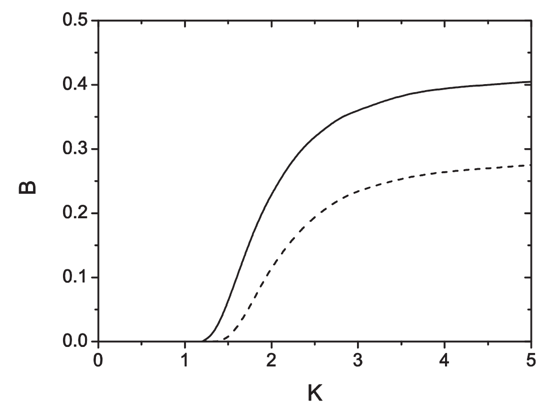


Fig. 4. Ratio of gain lengths for lasing at the fundamental wavelength and at the third harmonic versus diffraction parameter of the fundamental wavelength for large values of the undulator parameter K.

3D: $\Gamma \propto (A_{JJ}^2\omega^2)^{1/2}$

1D: $\Gamma_{1D} \propto (A_{JJ}^2\omega)^{1/3}$



Gain length of harmonic lasing

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$$L_g \simeq L_{g0}\,(1+\delta)$$ field gain length

$$L_{g0} = 1.67\left(\frac{I_A}{I}\right)^{1/2}\frac{(\epsilon_n\lambda_\mathrm{w})^{5/6}}{\lambda_h^{2/3}}\,\frac{(1+K^2)^{1/3}}{h^{5/6}KA_{JJh}}$$

$$\delta = 131\,\frac{I_A}{I}\,\frac{\epsilon_n^{5/4}}{\lambda_h^{1/8}\lambda_\mathrm{w}^{9/8}}\,\frac{h^{9/8}\sigma_\gamma^2}{(KA_{JJh})^2(1+K^2)^{1/8}}$$

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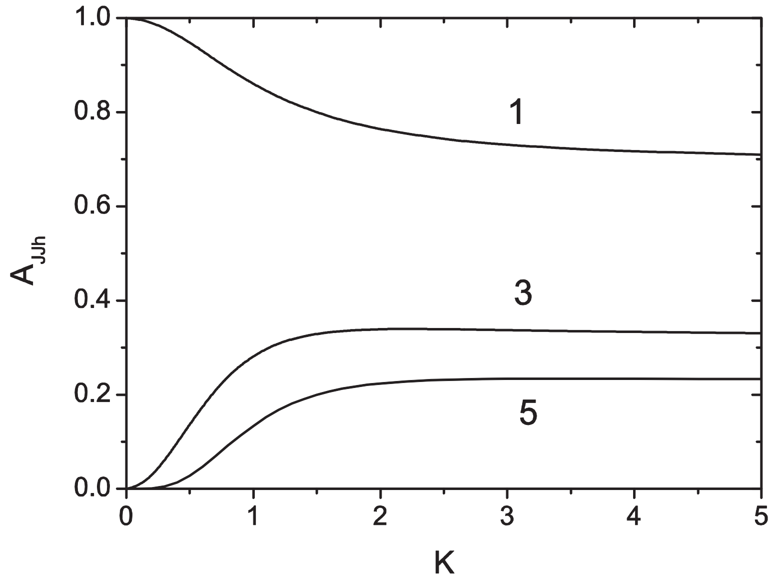

$$L_g(\beta) \simeq L_g(\beta_\mathrm{opt})\left[1+\frac{(\beta-\beta_\mathrm{opt})^2(1+8\delta)}{4\beta_\mathrm{opt}^2}\right]^{1/6}$$ for $\beta > \beta_\mathrm{opt}$ new also for the fundamental

$2\pi\epsilon/\lambda$ ~ 1 or $2\pi\epsilon/\lambda$ >> 1

Energy spread effects

Harmonics are more sensitive to energy spread due to a higher mobility of particles (larger R56' in the undulator)

However, a reserve in gain length in the case of no energy spread lets harmonics be competitive with the fundamental also when the energy spread effects are significant.

XFEL.EU: Lasing at 1 A with 0.5 nC (current 5 kA, emittance 0.7 um)

Changing K

	1st	3rd
Energy	10.5 GeV	10.5 GeV
$K_{\rm rms}$	1.05	2.3
Field L_g (no en. sp.)	10.4 m	6.9 m
Allowed en. sp.	2.8 MeV	

Changing energy

	1st	3rd
Energy	17.5 GeV	10.5 GeV
$K_{\rm rms}$	2.2	2.3
Field L_g (no en. sp.)	7.9 m	6.9 m
Allowed en. sp.	1.3 MeV	

Higher harmonics

Higher harmonics are doing better for a large K and no energy spread

At some point there is a cutoff due to energy spread

There are technical issues (undulator field errors, undulator wakefields etc.)

The 5th harmonic lasing can still be considered practical in many cases

Lasing at 1 A with 0.5 nC (current 5 kA, emittance 0.7 um)

Changing K

	1st	5th
Energy	10.5 GeV	10.5 GeV
K_{rms}	1.05	3.1
Field L_g (no en. sp.)	10.4 m	5.8 m
Allowed en. sp.	2.3 MeV	