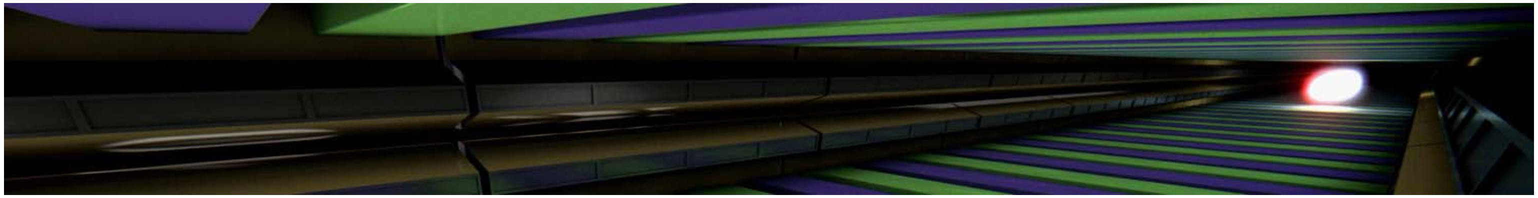
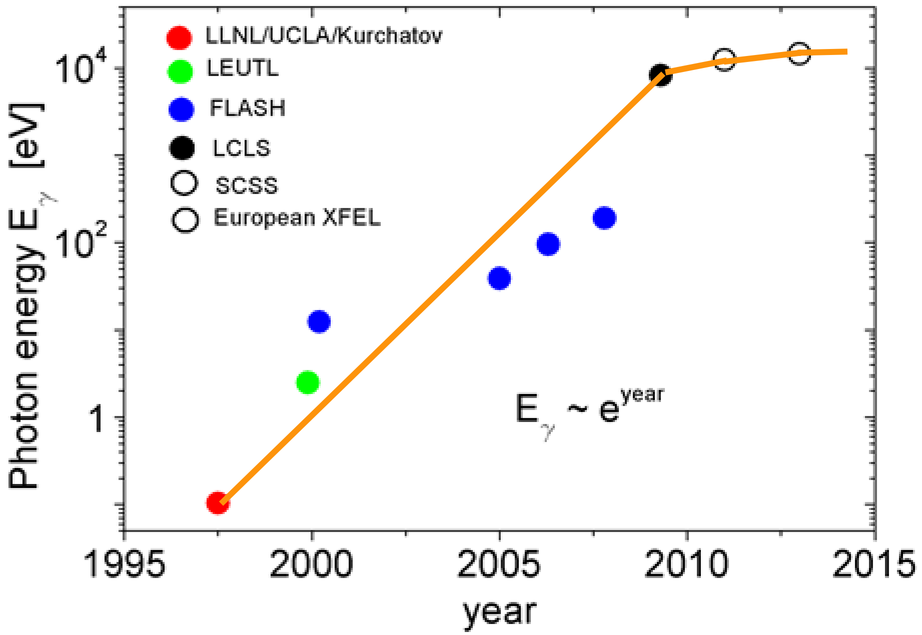


Expected properties of the radiation from SASE3

E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov

X-ray FELs: Where we are now?

- Race for achieving shortest SASE FEL wavelength is finished in spring of this year with successful operation of LCLS in Stanford at 0.15 nm.
- This is great success of the direction of x-ray SASE FELs: with careful design of accelerator, beam formation system, and undulator there is no problem to reach the target wavelength around 0.1 nm.
- The next problem is providing better quality of the radiation and wider possibilities for users experiments. That is exactly a target goal for the European XFEL.



X-ray FELs: What are the points of user's interest?

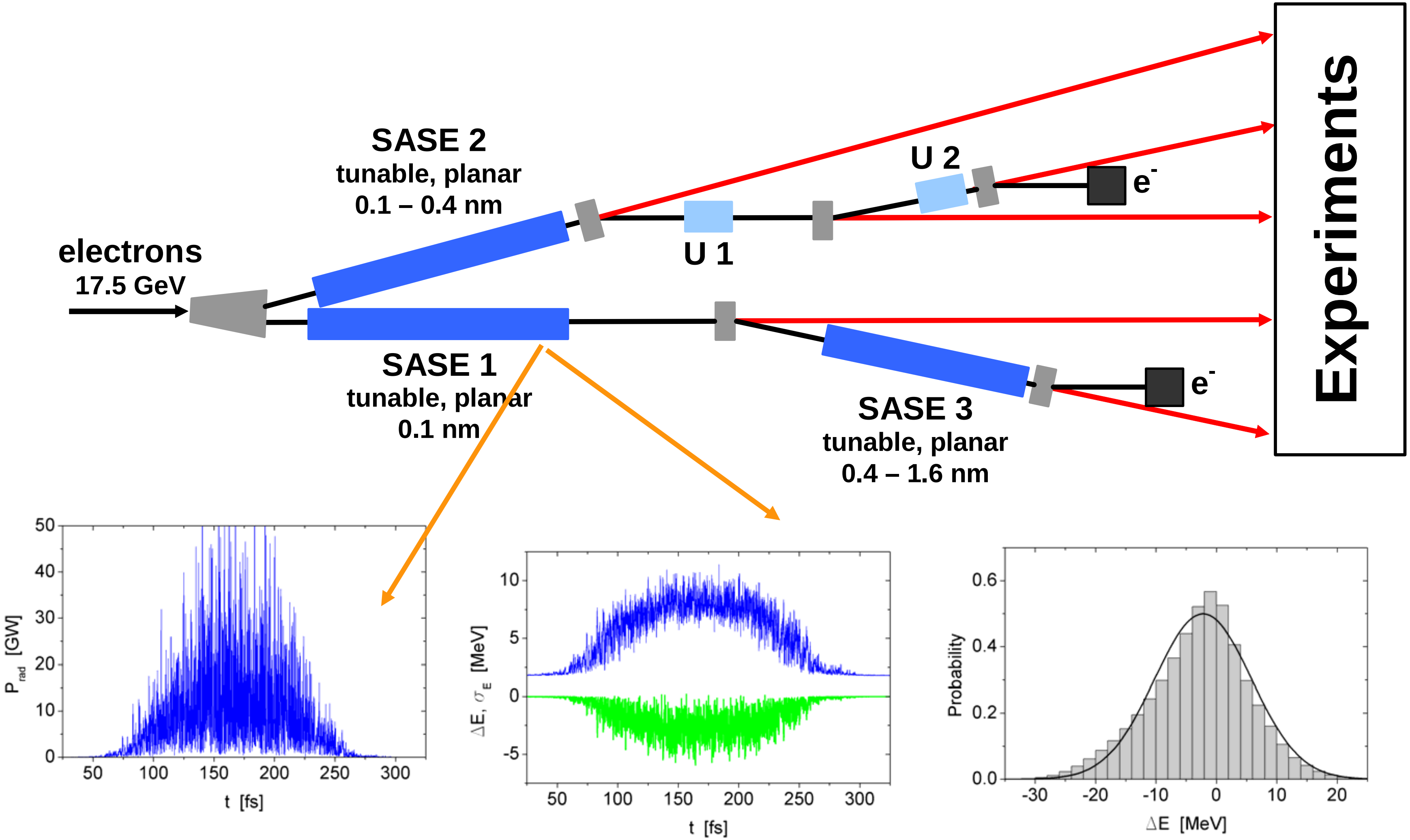
✓ Items highlighted in this talk mainly refer to the baseline parameter set of SASE3:

- Tunability of the wavelength.
- Temporal properties.
- Energy in the radiation pulse, peak and average power.
- Spectral properties.
- Temporal and spatial coherence.
- Polarization.

✓ A lot of other important items need to be discussed later on:

- Variation of temporal (spectral) properties of the radiation pulse.
- Organization of pump-probe experiments with ultimate (fs scale) temporal resolution.
- Multi-bunch features: macropulse repetition rate, # of bunches in a train, bunch separation, specific patterns of bunch filling in a train, etc.
- We invite users to formulate other specific requests. Note that the baseline option of the European XFEL is not a bible: accelerator and FEL techniques hold great potential for producing rather specific features of the radiation. If your requirements are compatible with physical laws and technical possibilities, you have a good chance for success.

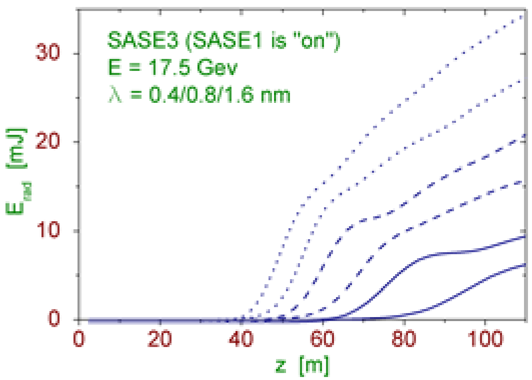
SASE3 @ European XFEL: an overview

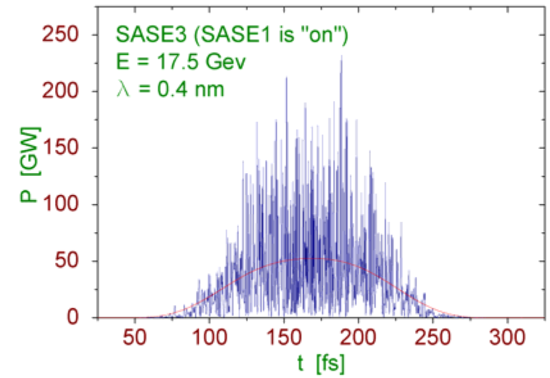


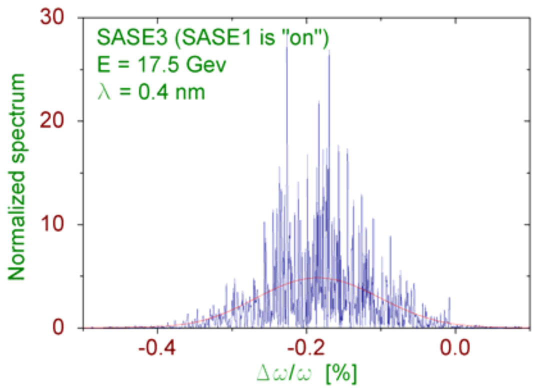
- SASE3 uses spent electron beam from SASE1

SASE3 @ European XFEL: nominal mode of operation

- Radiation energy
- Temporal structure
- Spectrum

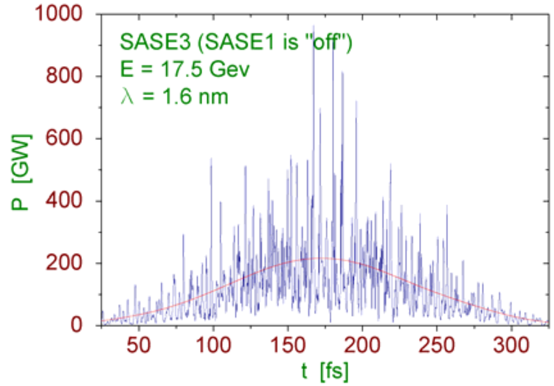


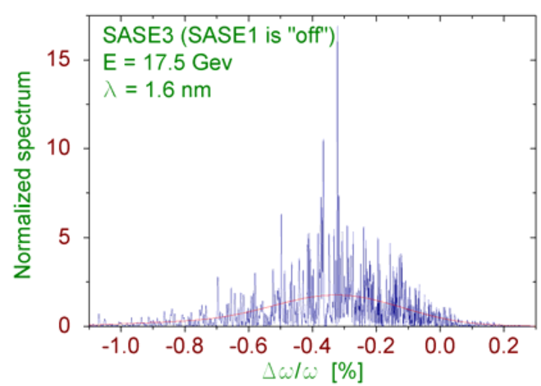




<u>Operation at 17.5 GeV:</u>

- Wavelength range 0.4 – 1.6 nm
- Pulse energy up to 35 mJ
- Average power up to 1 kW
- Peak power at sub-TW level
- Spectrum width 0.2 – 0.5 %
- Coherence time 0.3 - 0.9 fs





<u>Advantages of a high peak power are due to high energy of the driving electron beam</u>

SASE3 @ European XFEL: nominal mode of operation. Extended list of parameters

SASE3 @ 17.5 GeV

SASE3 (SASE1 is off)

Wavelength, nm	0.4	0.8	1.6
Pulse energy, mJ	7.8 (9.5)	12 (24.8)	16 (34)
Peak power, GW	78 (95)	120 (250)	160 (340)
Average power, W	234 (290)	360 (740)	480 (1020)
pulse duration (FWHM), fs	100	100	100
Angular divergence, μrad	3.2 (2.6)	5.8 (4.2)	10.2 (7)
Photon Beam size (FWHM), μm	52 (56)	62 (66)	64 (84)
Spectrum bandwidth (FWHM), %	0.2	0.26	0.32
ρ	1×10^{-3}	1.3×10^{-3}	1.6×10^{-3}
Saturation length, m	91	71	61
# photons/pulse	0.157×10^{14}	0.483×10^{14}	0.128×10^{15}
Peak flux [phot/s]:	0.157×10^{27}	0.483×10^{27}	0.128×10^{28}
Average flux [phot/s]:	0.471×10^{18}	0.144×10^{19}	0.386×10^{19}
Peak brillance	0.189×10^{34}	0.115×10^{34}	0.612×10^{33}
Average brillance	0.568×10^{25}	0.347×10^{25}	0.183×10^{25}

SASE3 (SASE1 is on)

Wavelength, nm	0.4	0.8	1.6
Pulse energy, mJ	6	10 (15.7)	14 (27)
Peak power, GW	60	100 (160)	140 (270)
Average power, W	180	300 (480)	420 (810)
pulse duration (FWHM), fs	100	100	100
Angular divergence, μrad	3.4	6. (4.4)	11.4 (6.6)
Photon Beam size (FWHM), μm	58	62 (64)	68 (80)
Spectrum bandwidth (FWHM), %	0.2	0.26	0.32
ρ	1×10^{-3}	1.3×10^{-3}	1.6×10^{-3}
Saturation length, m	110	81	64
# photons/pulse	0.120×10^{14}	0.402×10^{14}	0.112×10^{15}
Peak flux [phot/s]:	0.120×10^{27}	0.402×10^{27}	0.112×10^{28}
Average flux [phot/s]:	0.362×10^{18}	0.120×10^{19}	0.338×10^{19}
Peak brillance	0.145×10^{34}	0.964×10^{33}	0.536×10^{33}
Average brillance	0.437×10^{25}	0.289×10^{25}	0.160×10^{25}

SASE3: synchrotron radiation at 110 m undulator length
17.5 GeV, 1 nC, 30000 pps

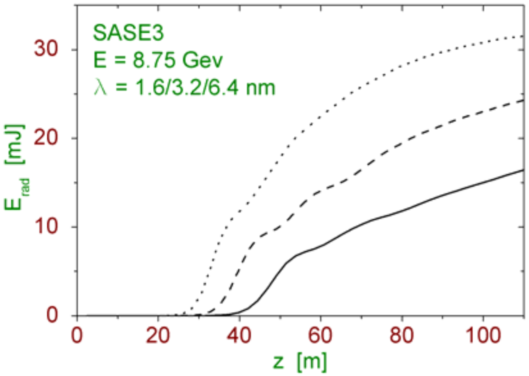
SR power average [W]:	467.013	968.780	1972.33
SR power peak [W]:	0.155×10^{12}	0.322×10^{12}	0.657×10^{12}
SR loss [MeV]:	15.5671	32.2927	65.7443
SR diffusion [MeV]:	1.73084	2.99178	5.09912

Data files are available in the following ways:

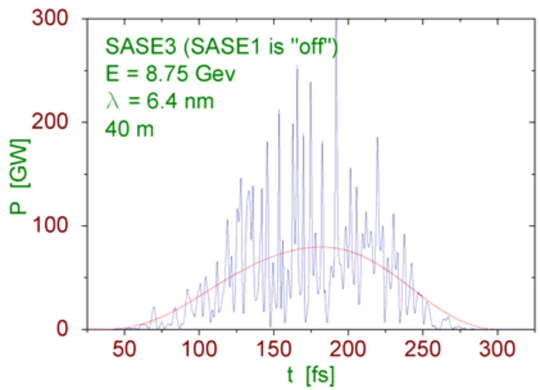
- Within internal DESY/XFEL network: \\win.desy.de\home\yurkov\public\SASE3-dataset-Feb09\
- Outside DESY/XFEL: web link is under construction, and you are cordially invited to request data files via E-mail: mikhail.yurkov@desy.de.

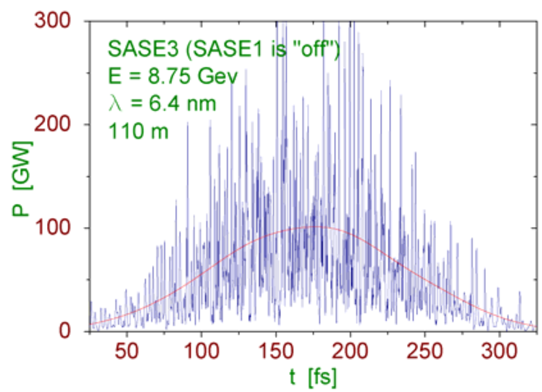
SASE3 @ European XFEL: operation in the “water window” and VUV wavelength range

■Radiation energy

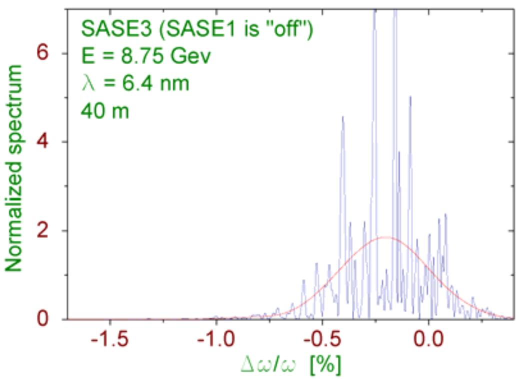


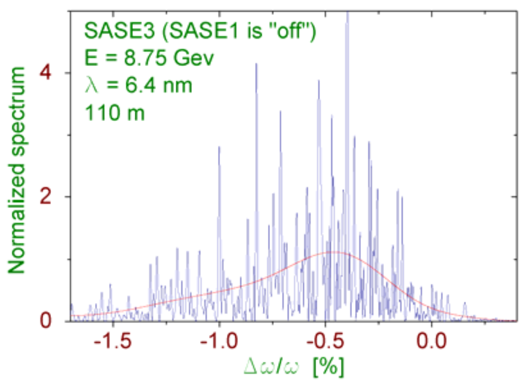
■Temporal structure





■Spectrum





<u>Operation at 8.75 GeV:</u>

- ■Wavelength range 1.6 – 6.4 nm
- ■Extremely high energy in the radiation pulse, about two orders of magnitude above project value of FLASH (500 uJ).
- ■Peak power at sub-TW level.

SASE3 @ European XFEL: operation in the “water window” and VUV wavelength range. Extended list of parameters

SASE3 @ 8.75 GeV

SASE3 @ 8.75 GeV (SASE1 is off)

Wavelength, nm	1.6	3.2	6.4
Pulse energy, mJ	7.5 (16)	9.5 (24)	12 (35)
Peak power, GW	75 (160)	95 (240)	140 (250)
Average power, W	225 (480)	285 (720)	360 (750)
pulse duration (FWHM), fs	100	100	100
Angular divirgence, μrad	8.8 (5.8)	16. (9.4)	30. (16.)
Photon Beam size (FWHM), μm	82 (102)	90 (136)	96 (168)
Spectrum bandwidth (FWHM), %	0.23	0.29	0.37
ρ	1.16×10^{-3}	1.46×10^{-3}	1.84×10^{-3}
Saturation length, m	58.5	47	37
# photons/pulse	0.604×10^{14}	0.153×10^{15}	0.386×10^{15}
Peak flux [phot/s]:	0.604×10^{27}	0.153×10^{28}	0.386×10^{28}
Average flux [phot/s]:	0.181×10^{19}	0.459×10^{19}	0.115×10^{20}
Peak brillance	0.405×10^{33}	0.204×10^{33}	0.102×10^{33}
Average brillance	0.121×10^{25}	0.612×10^{24}	0.307×10^{24}

SASE3: synchrotron radiation at 110 m undulator length
8.75 GeV, 1 nC, 30000 pps

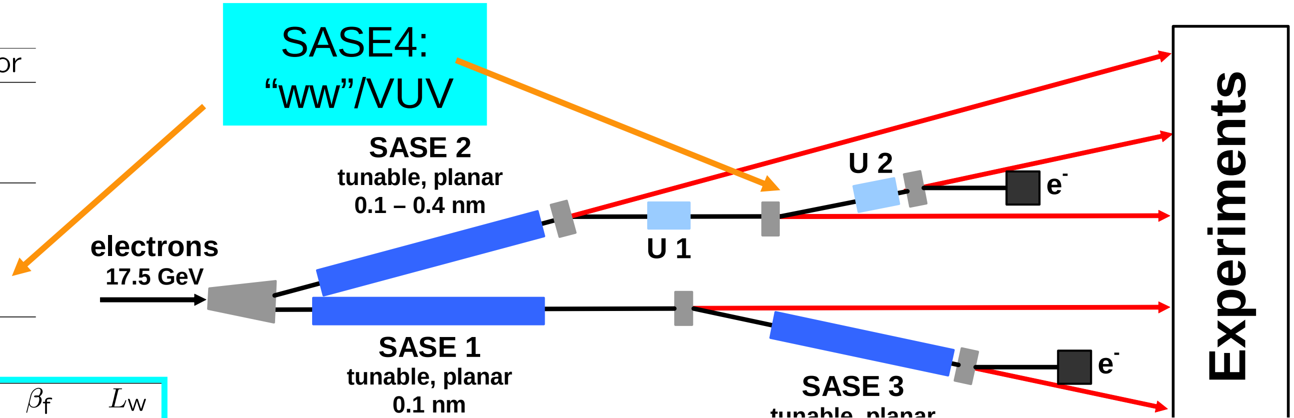
SR power average [W]:	116.753	242.195	493.082
SR power peak [W]:	0.389×10^{11}	0.807×10^{11}	0.164×10^{12}
SR loss [MeV]:	3.89177	8.07316	16.4361
SR diffusion [MeV]:	0.432711	0.747945	1.27478

Data files are available in the following ways:

- Within internal DESY/XFEL network: \\win.desy.de\home\yurkov\public\SASE3-dataset-Feb09\
- Outside DESY/XFEL: web link is under construction, and you are cordially invited to request data files via E-mail: mikhail.yurkov@desy.de.

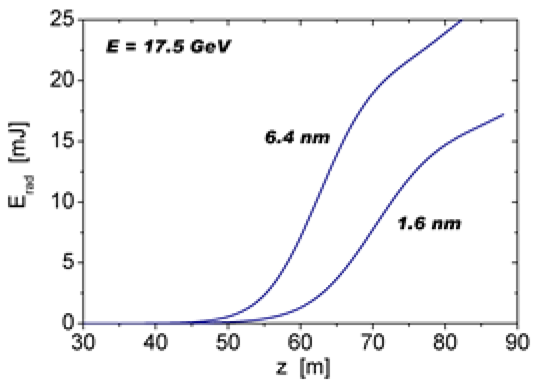
SASE4 @ European XFEL: do we need a dedicated beamline operating in the “water window” and VUV wavelength range (1.6 - 6.4 nm)?

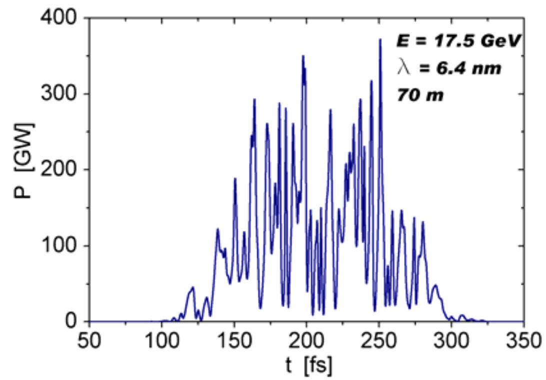
Location	Tunnel length	Undulator
XS1-XS3	620 m	SASE1
XS3-XHDU1	310 m	SASE3
XS1-XS2	550 m	SASE2
XS2-XS4	190 m	Spont.
XS4-XHDU2	250 m	Spont.



λ_r nm	λ_u mm	gap mm	B_w T	K_{rms}	β_f m	L_w m
1.6-6.4	110	19-37	0.7-1.6	5.7-12	10-20	80

	Units	Value
Wavelength range	nm	1.6/6.4
Peak power	GW	up to 150 GW
Average power	W	up to 800 W
Ph. beam size	μm	60/90
Ph. beam divergence	μrad	11/27
Saturation length	m	70/80

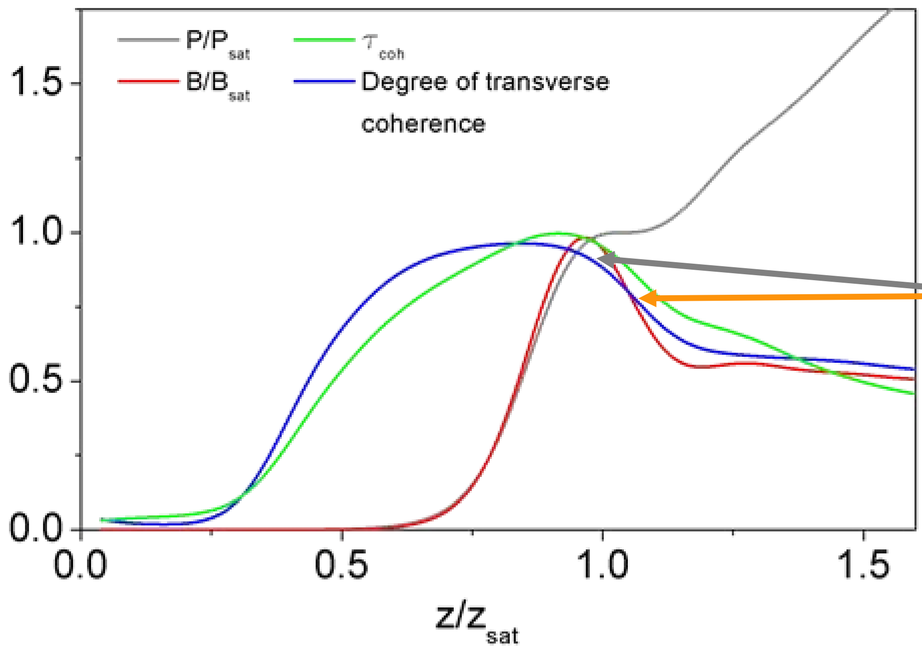


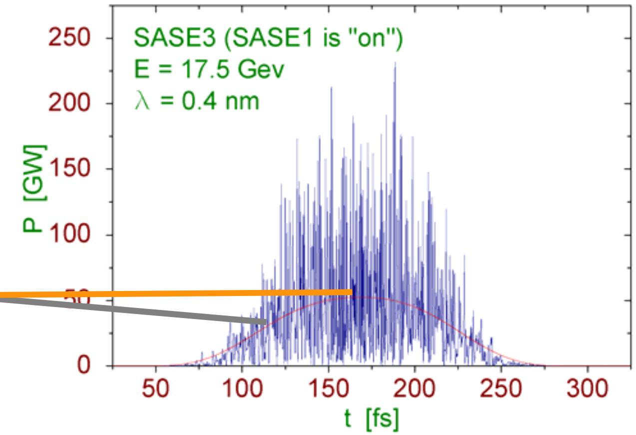


- Can be placed in one of the tunnels for spontaneous undulators U1 or U2.
- Can use spent beam after SASE2.
- Attractive feature: extremely high energy in the radiation pulse, about two orders of magnitude above project value of FLASH (500 uJ).

SSY, TESLA FEL 2004-02

SASE3 @ European XFEL: coherence properties





$$\gamma_1(\vec{r},\vec{r}') = \frac{\langle \tilde{E}(\vec{r},t)\tilde{E}(\vec{r}',t)\rangle}{\left[\langle|\tilde{E}(\vec{r},t)|^2\rangle\langle|\tilde{E}(\vec{r}',t)|^2\rangle\right]^{1/2}}$$

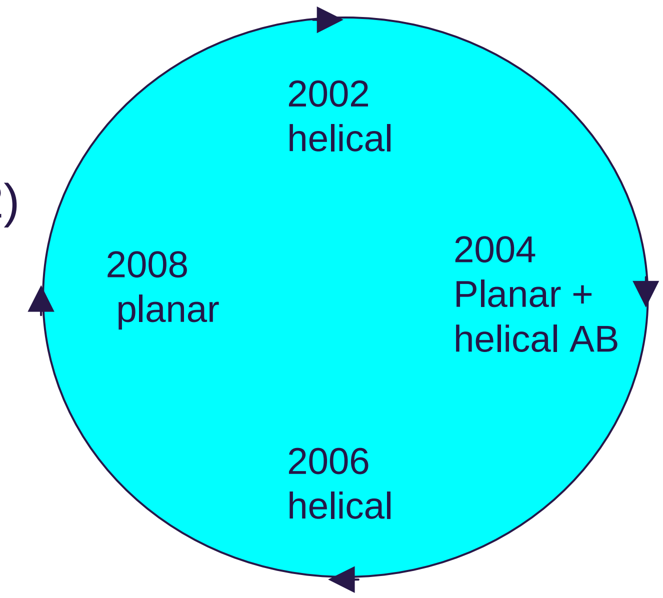
$$\zeta = \frac{\int\int|\gamma_1(\vec{r}_\perp,\vec{r}'_\perp)|^2\langle I(\vec{r}_\perp)\rangle\langle I(\vec{r}'_\perp)\rangle d\vec{r}_\perp d\vec{r}'_\perp}{[\int\langle I(\vec{r}_\perp)\rangle d\vec{r}_\perp]^2}$$

- Degree of transverse coherence and coherence time reach their maxima in the end of the linear regime, and degrade drastically in the nonlinear regime.
- Situation is complicated due to gradient profile of the electron bunch. While tails of the photon pulse reach saturation, the core of the pulse is oversaturated, and degree of transverse coherence of the most intensive fraction of the pulse falls down.
- Operation with relatively high degree of transverse coherence (~80-90%) is possible only when the core of the electron bunch just enters nonlinear regime ➔ low pulse energy and maximum fluctuations of the radiation energy.

SSY, Opt. Comm. 281(2008)1179; Opt. Comm. 281(2008)4727

SASE3 @ XFEL: polarization of radiation

- Radiation of SASE FEL is nearly completely polarized. Polarization is linear for a planar undulator, and circular for a helical one.
- The first versions of TDR (TESLA 2001 and XFEL 2002) assumed helical undulator for SASE3.
- An option of planar version of SASE3 has been proposed to STI in 2004 with suggestion for realization at the earliest stage of the project. Concepts of crossed planar undulators and a helical afterburner have been discussed as well.
- Final version of TDR (2006) included only helical option for SASE3 with realization on a later stage of the facility construction.
- A decision on a planar structure of SASE3 has been taken in the autumn of 2007. It has been also decided to upgrade SASE3 in the future for production of circularly polarized radiation in the future.



SASE3 @ XFEL: production of circular polarization

Possible technical solutions for generation of circularly polarized radiation:

1) Option with helical afterburner. May operate at a high power.

2) Two full-length undulators and application of SASE switchers. May operate at a high power.

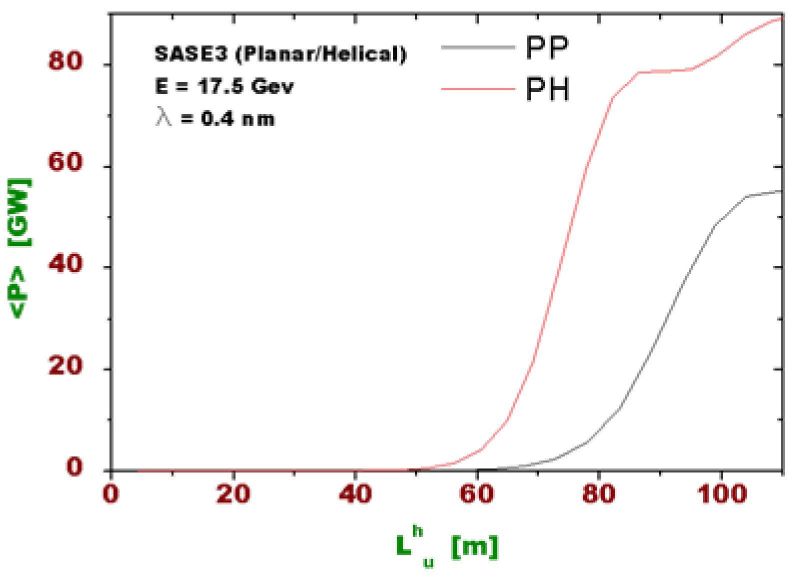
3) Option with cross-planar afterburner: two short, cross-planar undulators are installed after the main undulator. Operates at a low power level only (details are in the next talk by Y. Li).

4) Frequency doubler. May operate at a high power (TESLA FEL 2004-02). First undulator is a planar one. Helical undulator is tuned to double frequency. Linear and helical polarization are separated with dispersive optical elements.

5) Self-seeding option based on planar undulators. May operate at a high power. Photon pulse has complete longitudinal coherence. Seeding section is planar undulator, and radiating section consists of two crossed planar undulators.

SASE3 @ XFEL: circular polarization at full power and with high degree of coherence

Planar + helical option with full length undulators: tunnel length would allow to accommodate both options in a row. SASE in the proceeding undulator will be switched on/off with SASE switchers (SSY, TESLA FEL 2004-02). Planar undulator is installed first, and a helical one later on. Photon beams with planar and helical polarization at full power would be available.



Location of undulators on XFEL site

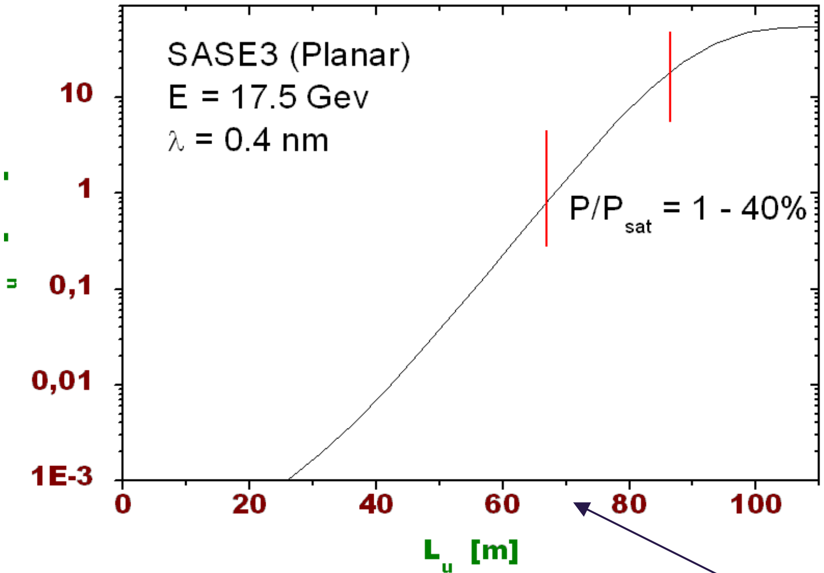
Location	Tunnel length	Undulator
XS1-XS3	620 m	SASE1
XS3-XHDU1	250 m	SASE3
XS1-XS2	550 m	SASE2
XS2-XS4	190 m	Spont.
XS4-XHDU2	250 m	SASE4

planar | helical

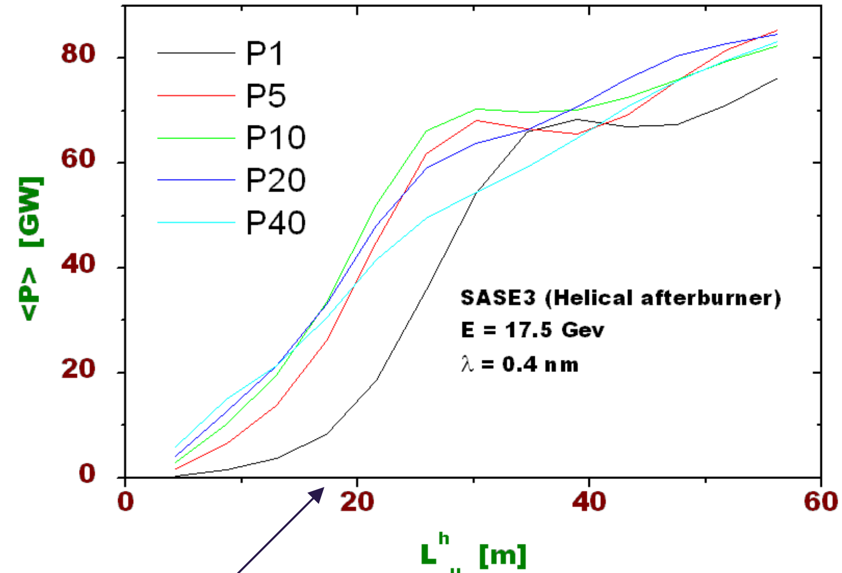
Problem: technical feasibility of helical undulator with required accuracy of magnetic field.

SASE3 @ XFEL: circular polarization at full power and with high degree of coherence

Planar undulator



Helical undulator



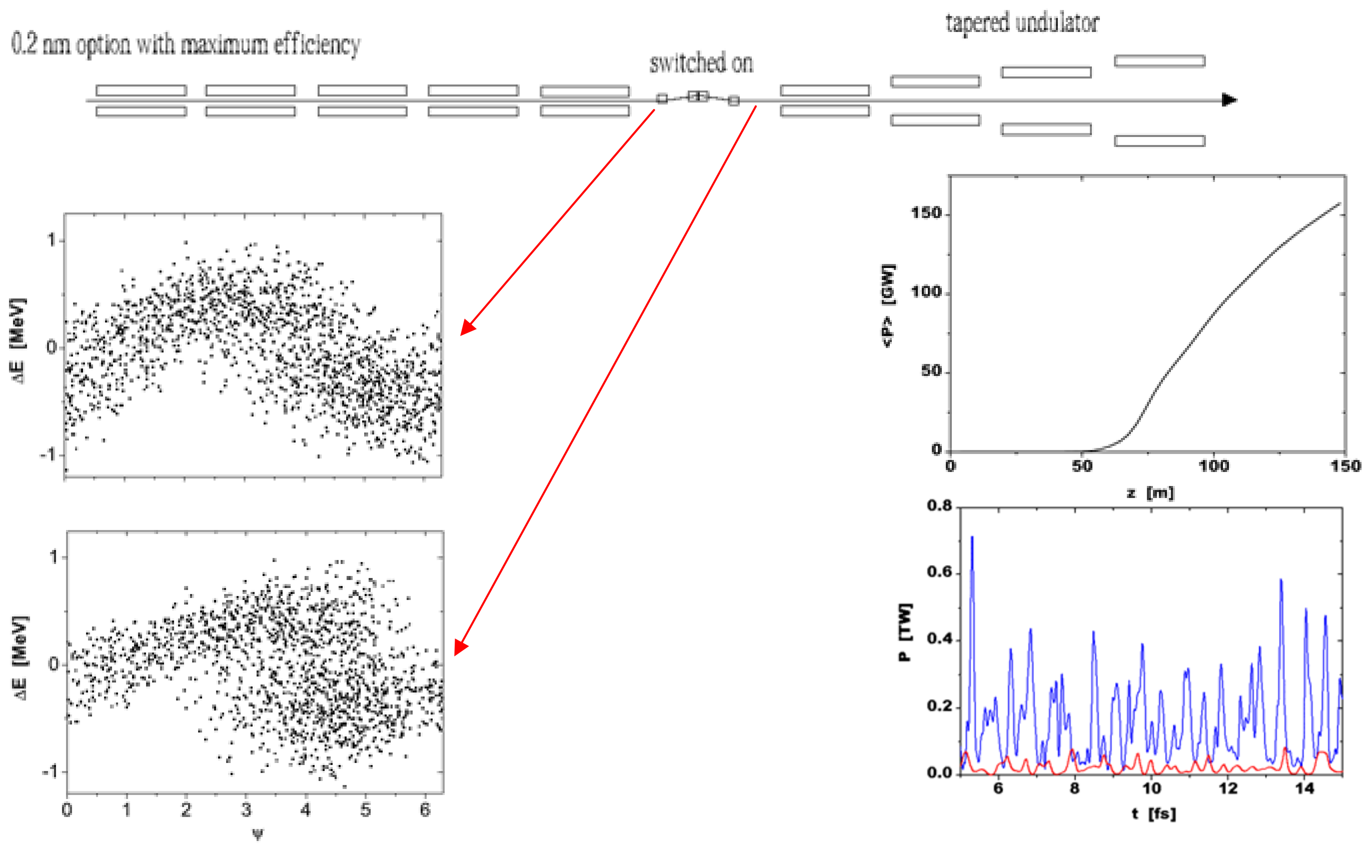
planar

helical

- Helical afterburner. Electron beam gains density modulation in the planar undulator. This density modulation (scalar quantity) serves as a seed for FEL process in the helical undulator producing radiation with helical polarization.
- 30 meters of helical undulator is sufficient to reach full saturated power with circular polarization at 0.4 nm, and about 15 meters at 1.6 nm. At a per cent level of P/Psat there is no need to suppress radiation from a planar undulator.

Thank you very much !

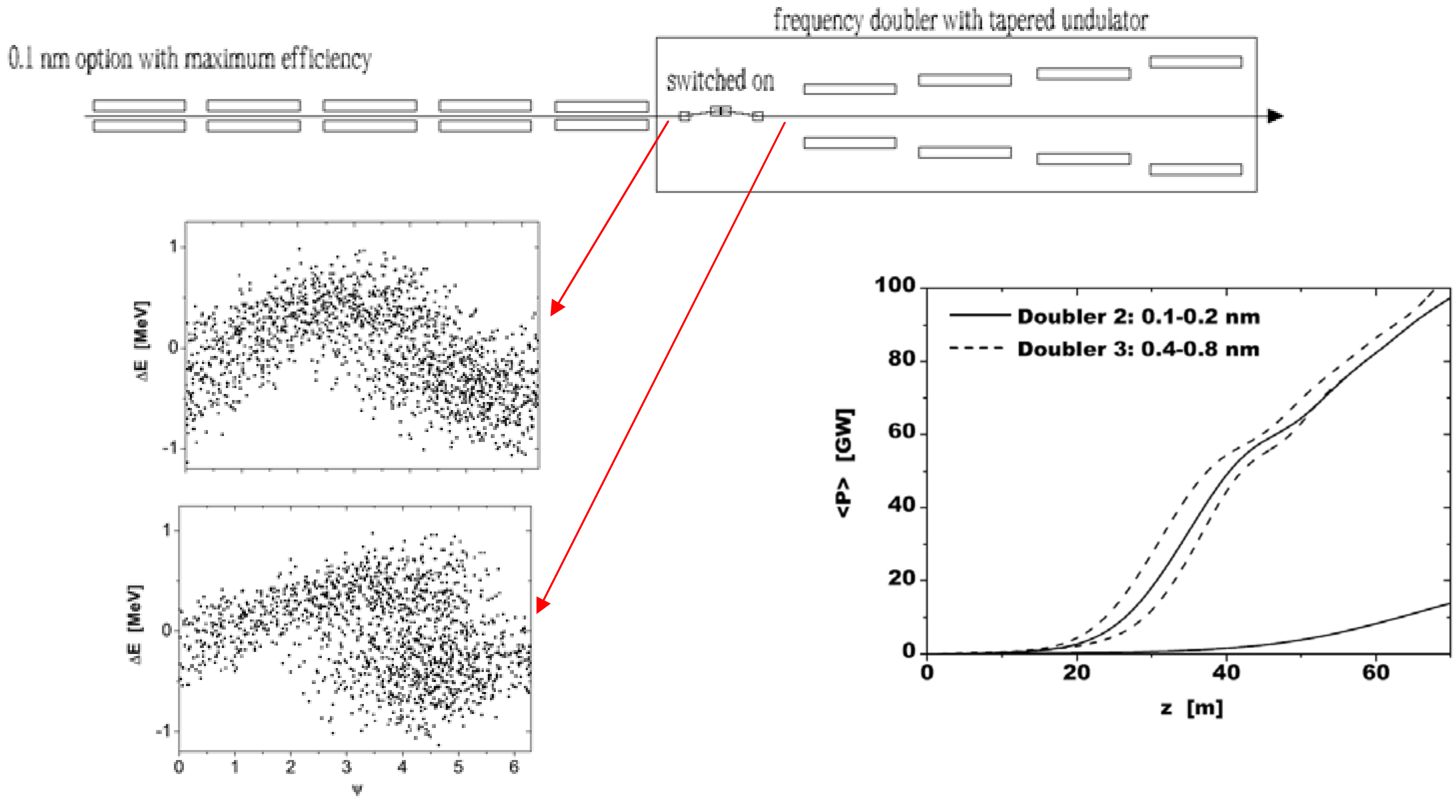
High power (sub-TW) mode of operation



- Use of a dispersion section for effective beam bunching;
- Application of undulator tapering for effective increase of radiation power in the nonlinear regime.

SSY, TESLA FEL 2004-02

Two-color mode of operation



- Use of a dispersion section for effective beam bunching at the 2nd harmonic;
- 2nd part of the undulator is tuned to the second harmonic;
- Application of undulator tapering for effective increase of radiation power in the nonlinear regime.

SSY, TESLA FEL 2004-02