Simulations and performance study of an optimized longitudinal phase space for the hard X-ray self-seeding at the European XFEL

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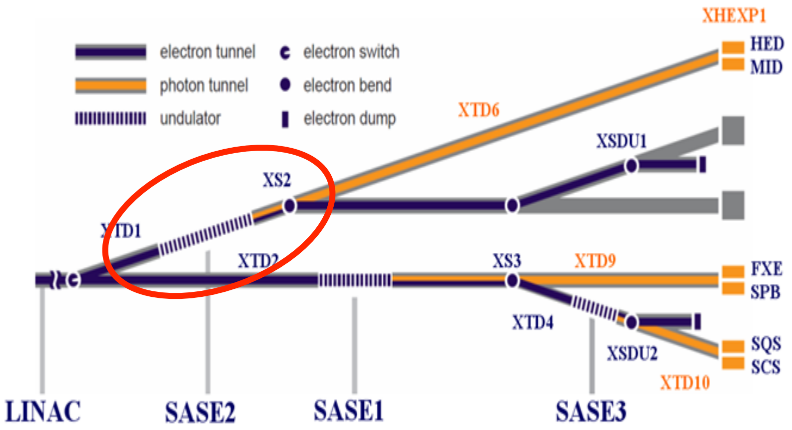
Future Light Sources Workshop, 05-09 March, 2018

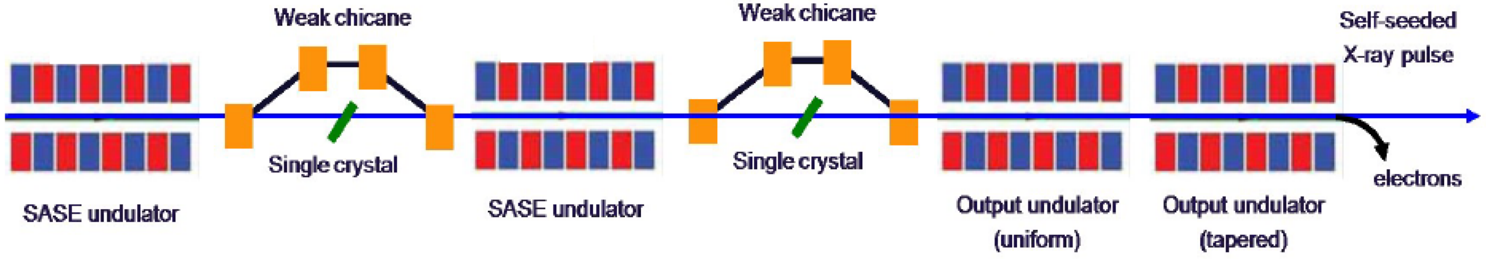
Outline

- HXRSS design at European XFEL
  - Principle and specialities
  - Challenges for HXRSS implementation (heat load, halo and linearity of long. PS)
- Longitudinal phase space optimization for HXRSS
- HXRSS simulations
  - Upper limit: 17.5 GeV e^-, 14.4 keV X-ray (chicane positions, tolerance study)
  - Lower limit : 8 GeV e^-, 3.5 keV X-ray (SNR)
- Schedule for HXRSS implementation and commissioning
- Summary and perspects

HXRSS design at European XFEL

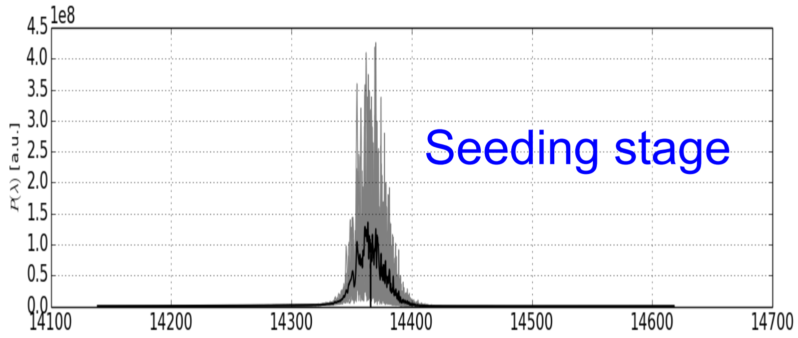
G. Geloni, V. Kocharyan, E. Saldin (*DESY 10-133*)

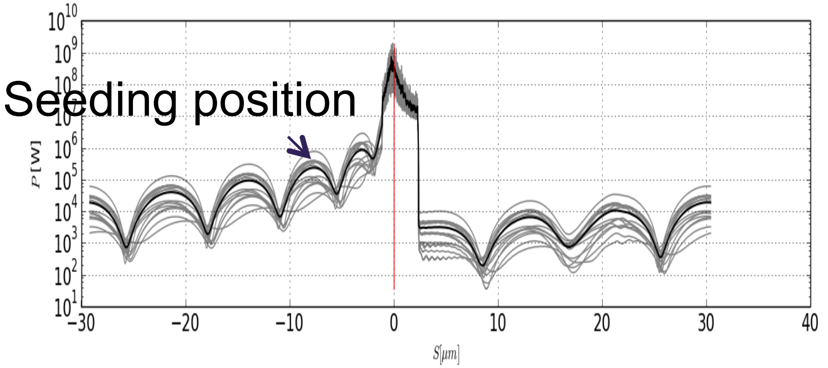




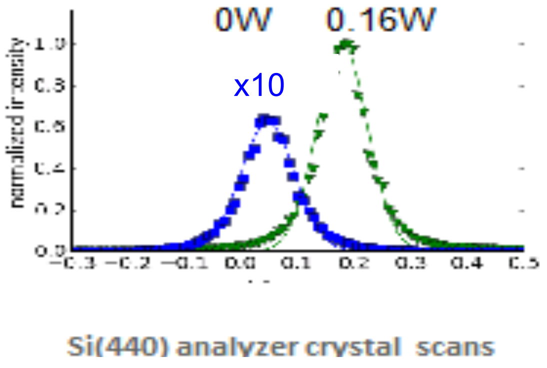
SASE2 line (3 keV -25 keV) will be first equipped with HXRSS

- Two stages: share the heat load on crystal and increase SNR
- Combination of high rep-rate HXRSS and Tapering
- Long undulators (35x5m magnetic length) → HXRSS+tapering
  - HXRSS: decreases bandwidth
  - Tapering: increases power
- Short bunches (FWHM<50 fs) are preferred (longer bunches -> larger spatio-temporal coupling effect)





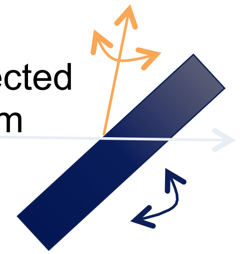
Challenge 1: heat load



X-ray reflection energy shift due to heat load $\Delta E/E = 3.1$ e-4

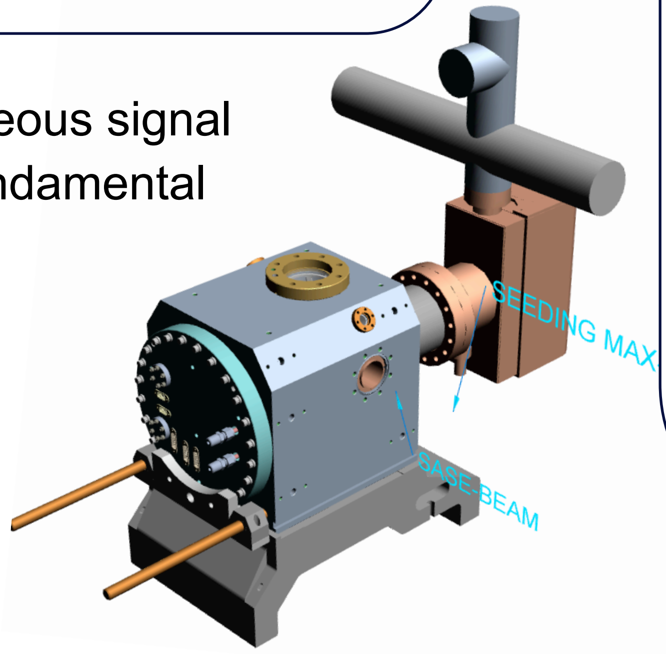
Experiment by L. Samoylova (European XFEL)

Courtesy of *H. Sinn*



Frequency (Hz)	Angular Range (PV)
1200	70 urad
…	…
300	280 urad
…	…
10	0.48°

- Heat-loading from the spontaneous signal
  → basically independent of the fundamental
  → broad spectrum

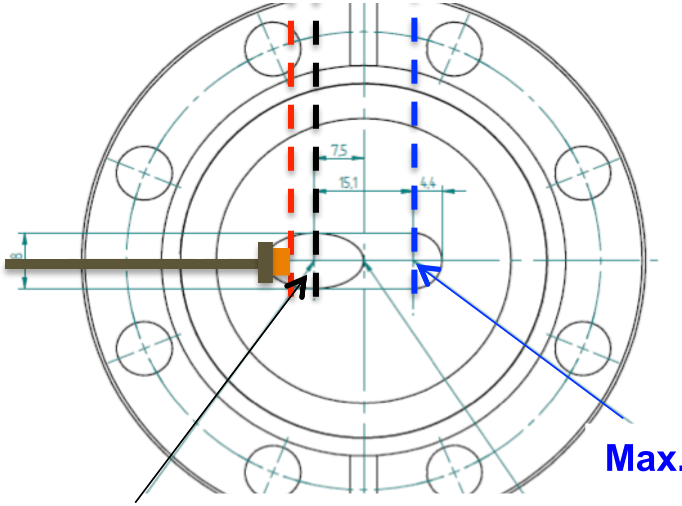


- Water cooling is foreseen
- Pitch oscillator will be treated as option (space foreseen and some development within design contract).
- Oscillate bragg angle can be used to compensate temperature cycle during pulse train.

- Chamber design: *T. Wohlenberg (DESY)*
- Diamond and holder design: *D. Shu (ANL), S. Terentiev (TISNUM)*

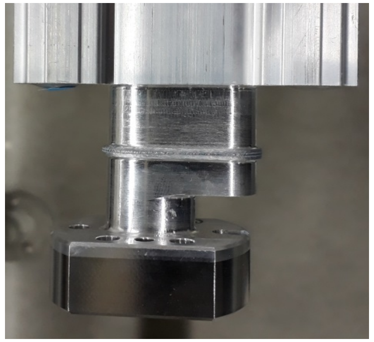
Challenge 2: beam halo

How close we can put the crystal to the e^- beam?

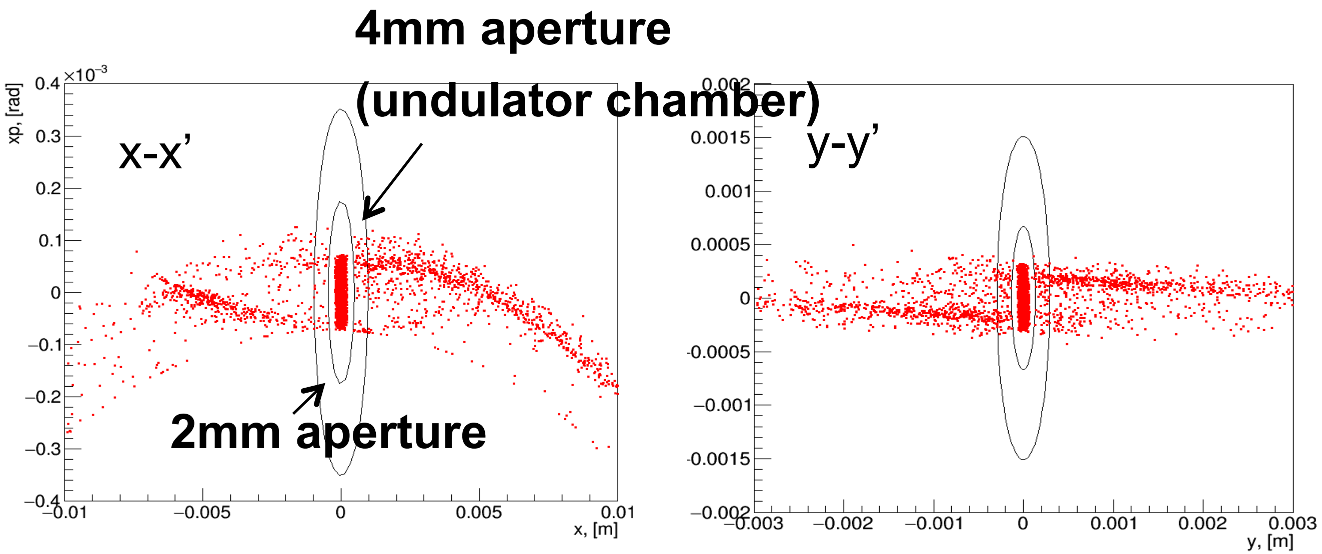


Center of undulator system (beam w/o seeding)

Max. e^- beam offset of 15 mm



- Chicane **maximum delay**: **~400 fs** (with 8-12 GeV e-) for **2-colour SASE**

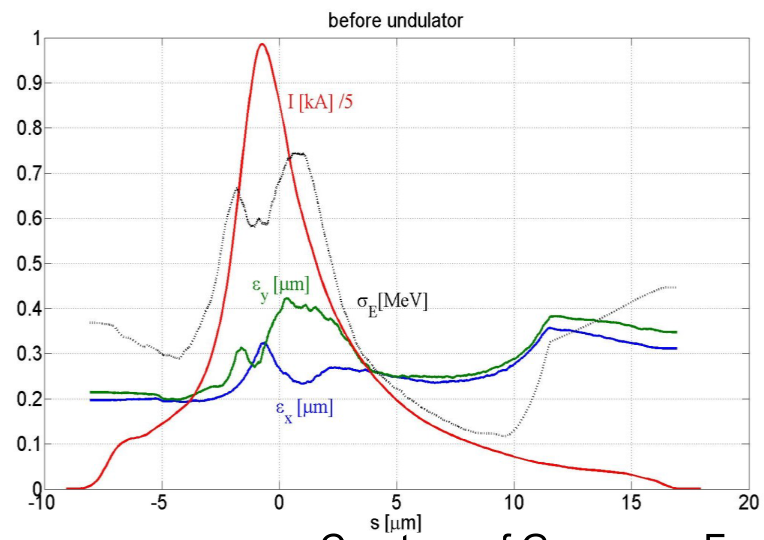


Simulated phase space distributions **at the end of the collimation section** for the X and Y plane with 10^6 input e^- halo (± 50 σ)

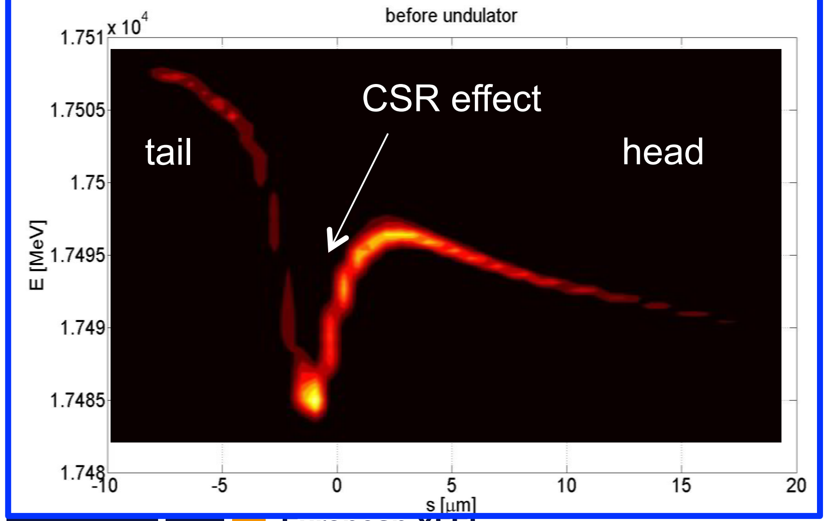
- The e^- between the R=2 mm and R=4 mm apertures (N_{hits}) are those which may hit the crystal
- N_{hits}/N_{total} **≈3×10^{-5} < 1×10^{-4}** (critical ratio for undulator damage)*
- The crystal can be inserted up to a distance of ~2 mm to the beam core (**~13 fs of minimum delay**) !

***S. Liu et al., in Proc. IPAC'17, paper WEPAB020**

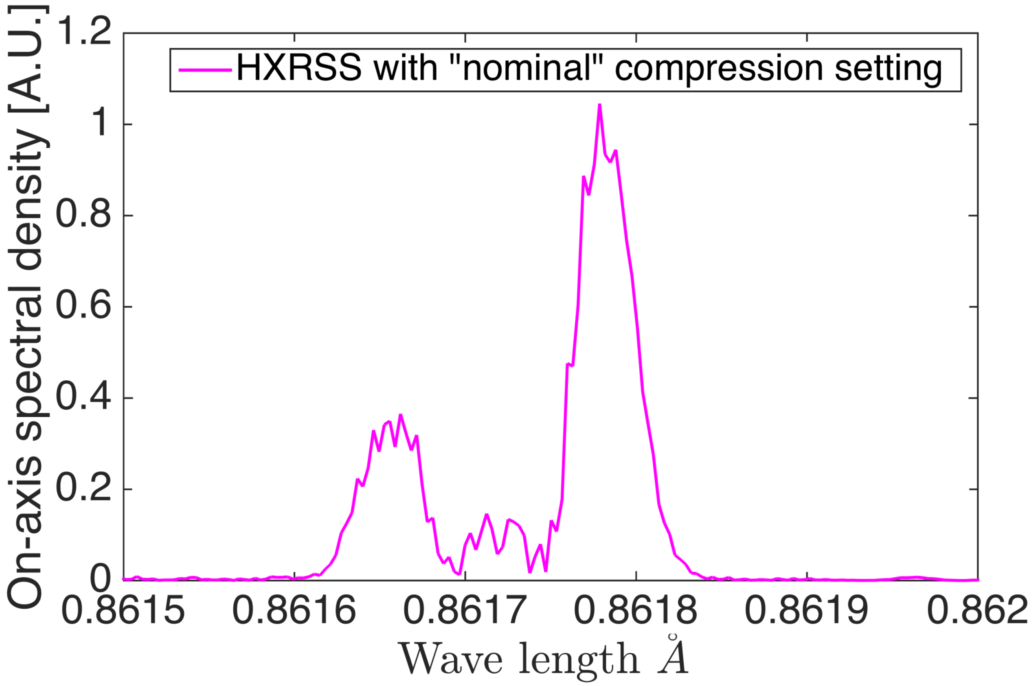
Challenge 3: linearity in longitudinal phase space



Courtesy of Guangyao Feng

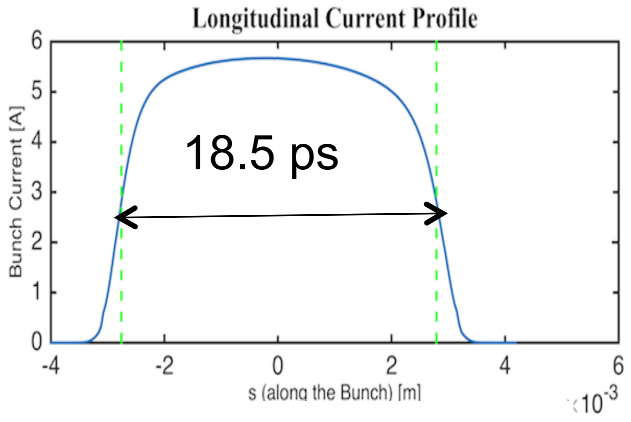


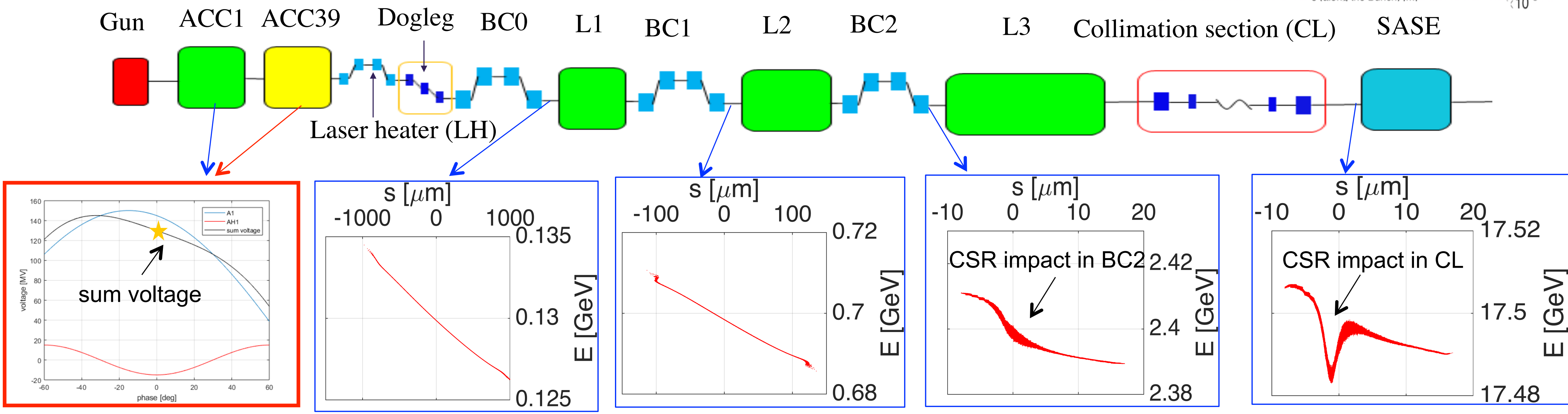
- 17.5 GeV, 100 pC e⁻ beam distribution before undulator (from S2E simulation with nominal compression)
- Nonlinear energy chirp before undulator decreases the HXRSS peak power and increases the HXRSS bandwidth (especially for high photon energies, e.g. 14.4 keV)



Longitudinal phase space along the beamline

- Distribution from gun: flat top (18.5 ps FWHM)
- Astra used for straight sections
- CSR track used for sections with bends (LH, dogleg, compressors, CL section)





- **Flat-top** current distribution (**increase of σ_z**)

-> **mitigate** the **CSR effect** in the collimation section

-> **mitigate** the **distortion** in longitudinal phase space

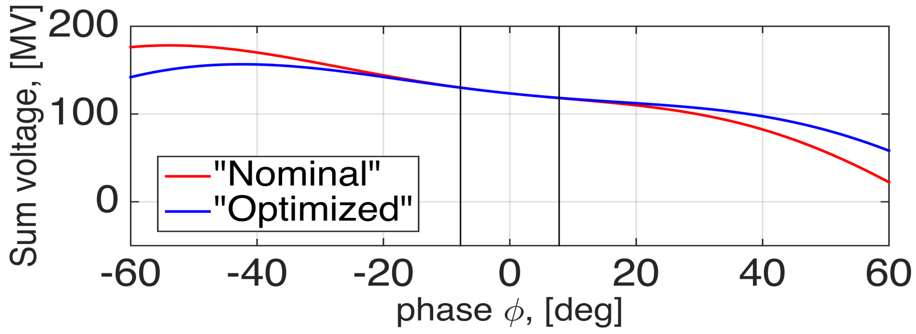
Longitudinal phase space optimization procedures

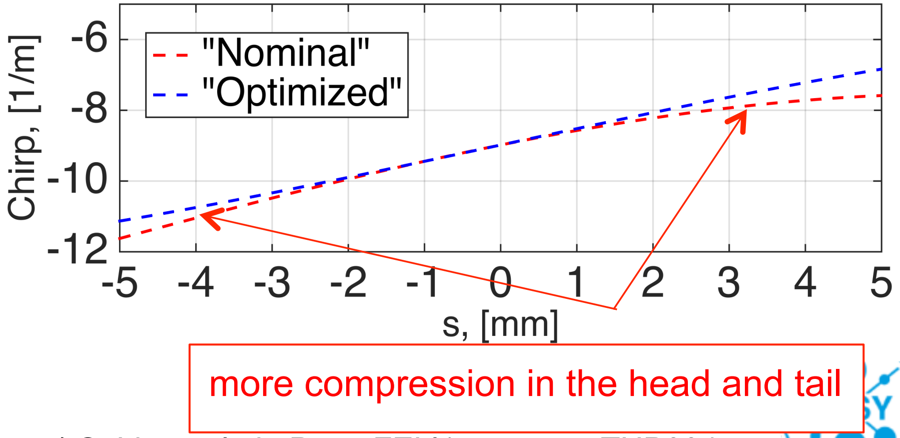
$$\begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & -k & 0 & -(nk) \\ -k^2 & 0 & -(nk)^2 & 0 \\ 0 & k^3 & 0 & (nk)^3 \end{bmatrix} \bullet \begin{bmatrix} V_{1,1}\cos\phi_{1,1} \\ V_{1,1}\sin\phi_{1,1} \\ V_{1,3}\cos\phi_{1,3} \\ V_{1,3}\sin\phi_{1,3} \end{bmatrix} = \begin{bmatrix} 1 \\ p_0^{'(1)} \\ p_0^{''(1)} \\ p_0^{'''(1)} \end{bmatrix}$$

- 3rd deviation p_0'''->flatness of current distribution (FWHM)
- 2nd deviation p_0''-> symmetry of current distribution
- 1st deviation chirp p_0'-> change compression (keep 5kA of peak current)

	$V_{1,1}$ MV	$\phi_{1,1}$ deg	$V_{1,3}$ MV	$\phi_{1,3}$ deg	P' m^{-1}	P'' m^{-2}	P''' m^{-3}
Nominal	156.7	18.0	25.6	184.1	-8.98	463.05	-226.3
Optimized	173.1	30.9	29.3	211.5	-8.98	437.06	-5.05e4
	V_2 MV	ϕ_2 deg	P_2' m^{-1}	V_3 MV	ϕ_3 deg	P_3' m^{-1}	V_4 MV
Nominal	639.6	27.2	-11.4	1.832e3	21.5	-7.6	1.51e4
Optimized	641.7	27.6	-11.6	1.832e3	21.5	-7.6	1.51e4

17.5GeV, 100pC, 5kA case. Optimization performed with RF tweak 5**





*M. Dohlus and T. Limberg, FEL'05, p.250. **Bolko Beutner, FEL Seminar 17.2.2015
***Igor Zagorodnov and Martin Dohlus, Phys. Rev. ST Accel. Beams 14, 014403 (2011)

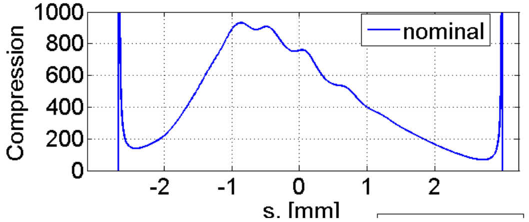
* S. Liu et al., in Proc. FEL'17, paper TUP004

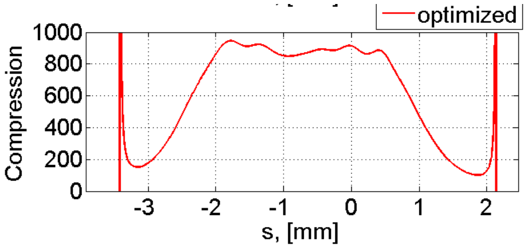
Longitudinal phase space optimization for HXRSS

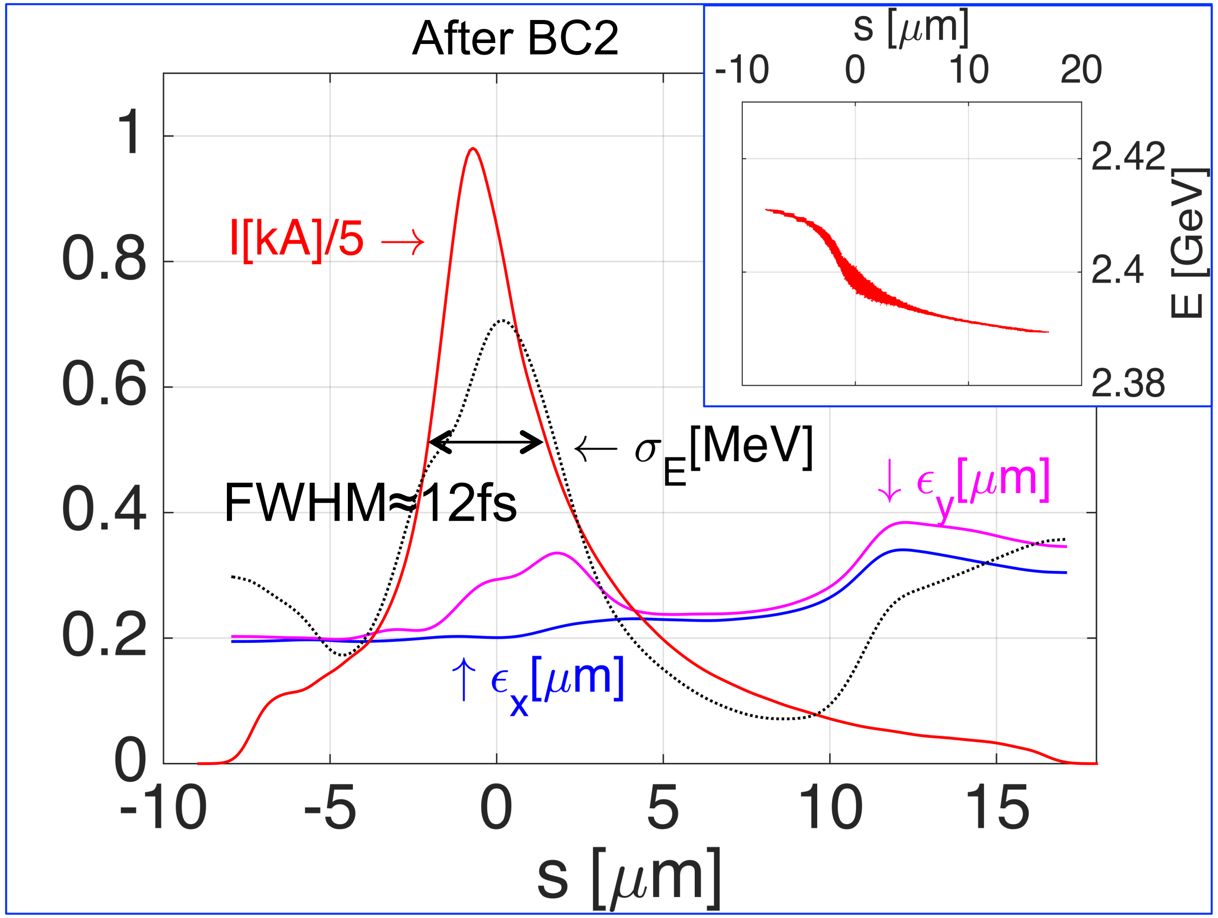
- After BC2, the global compression is more flat after optimization
- FWHM bunch length is increased from 12 fs to 15 fs, keeping the same peak current (5 kA)

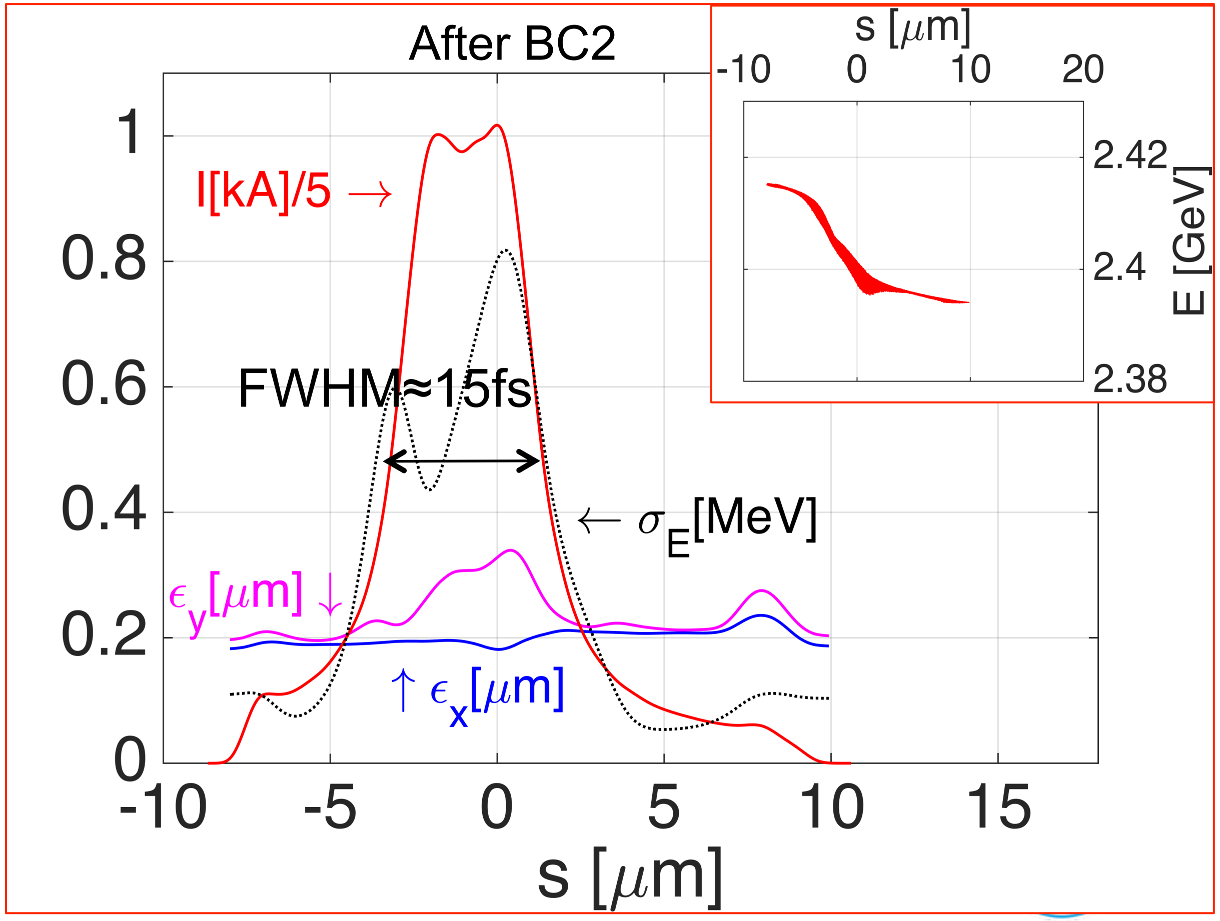
Before Optimization

After Optimization





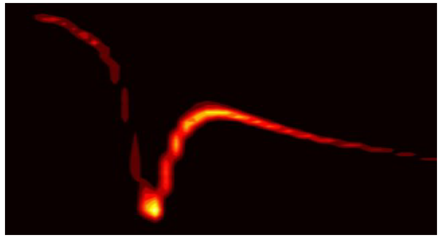




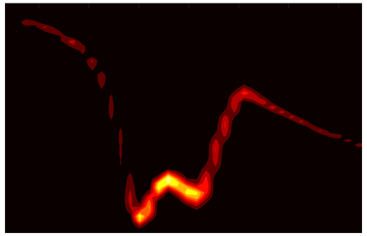
Longitudinal phase space optimization for HXRSS

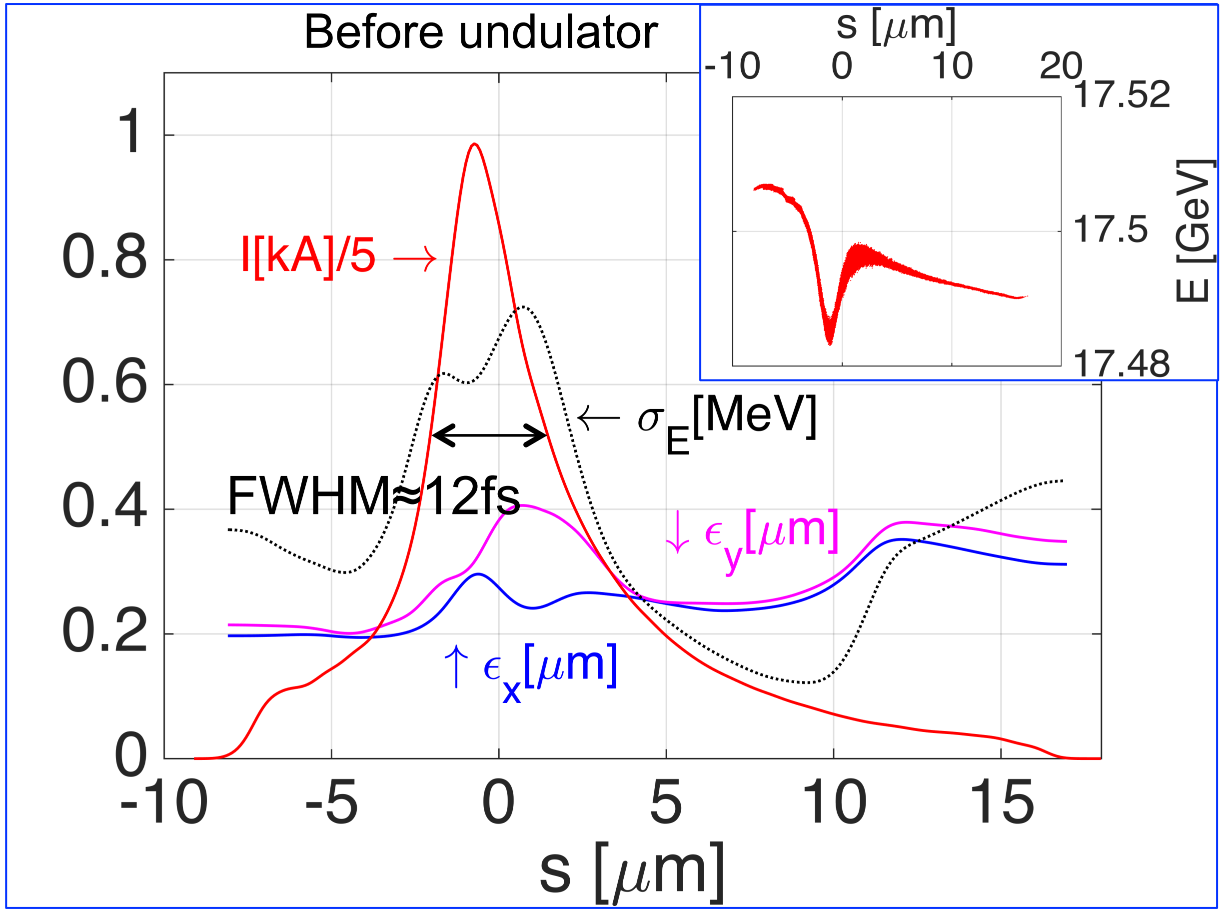
- A small double-horn structure is formed in the long. PS (due to CSR effect in the collimation section)

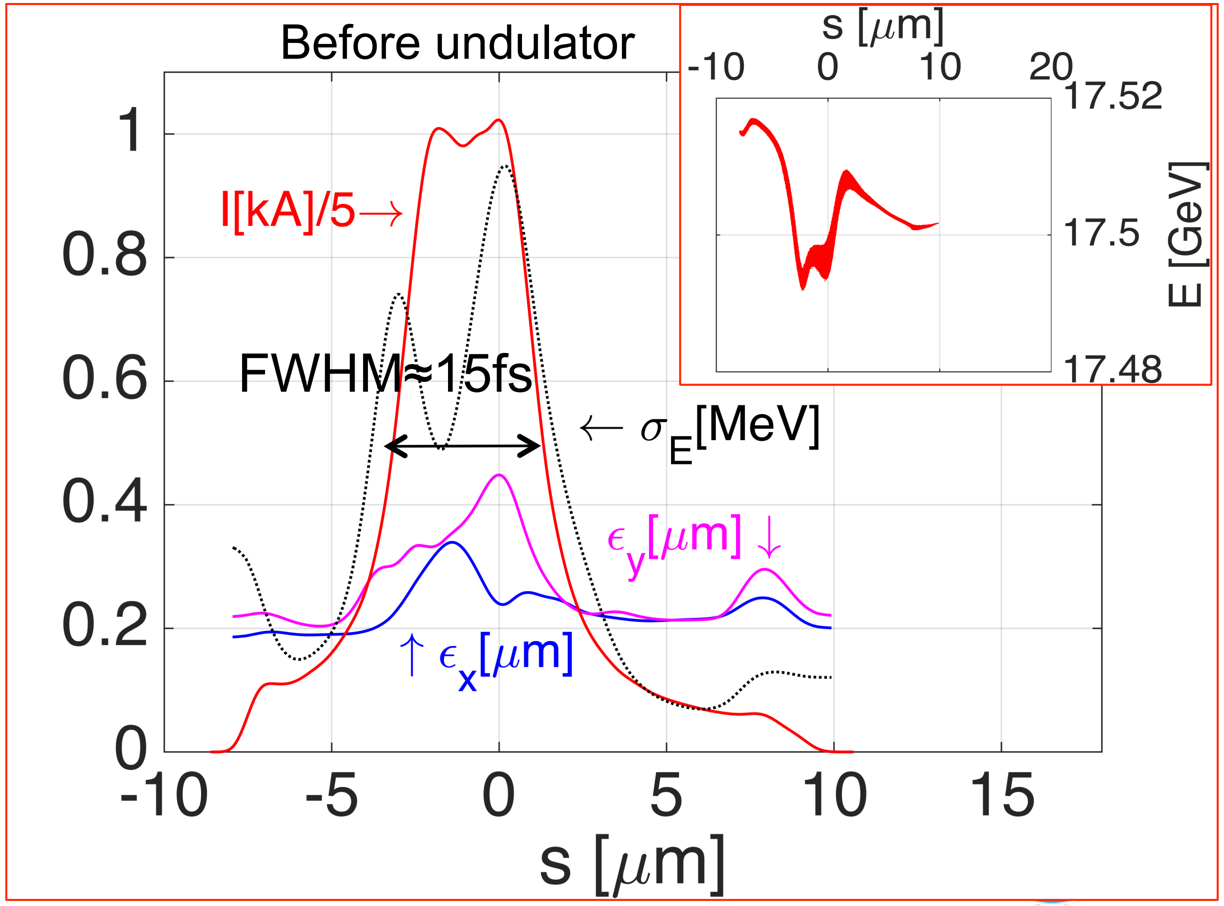
Before Optimization



After Optimization

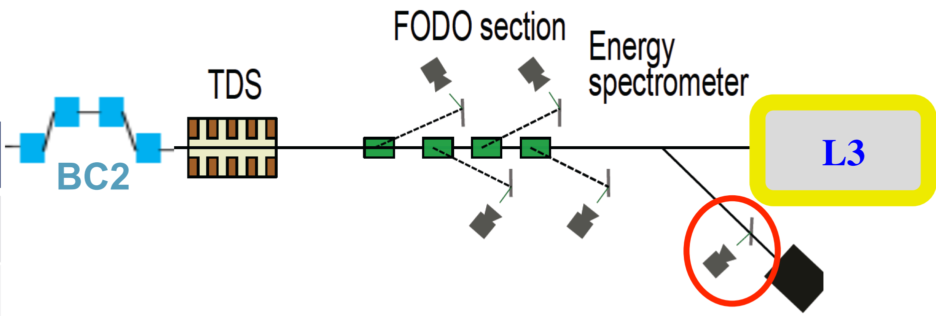


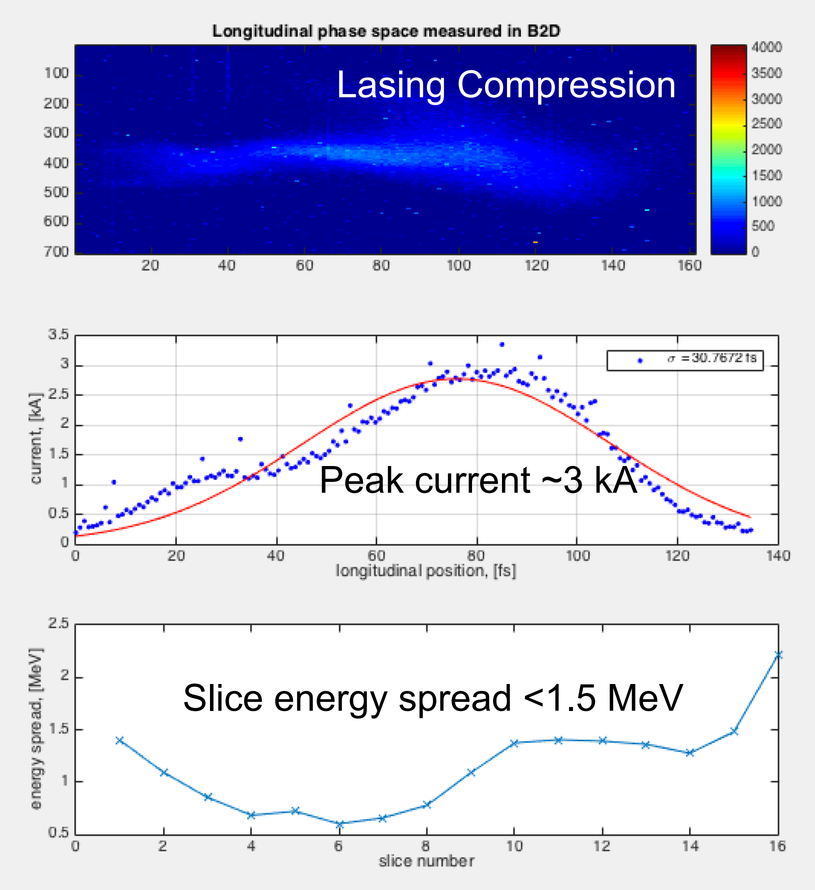


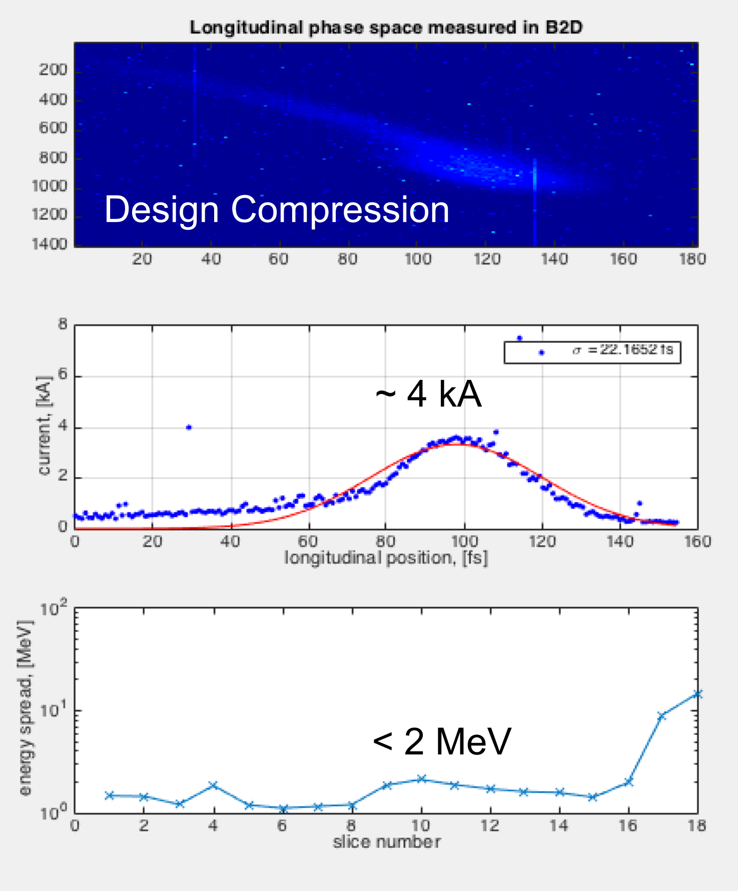


Example of first measurements of long. PS (250 pC)

	Chirp P_0'	Curvature P_0''	3rd derivative P_0'''	Chirp P_1'	Chirp P_2'
Lasing	-8.75	+138.6	+36970	-8.75	-1.75
Design	-8.50	+260.0	+60001	-8.58	-11.51



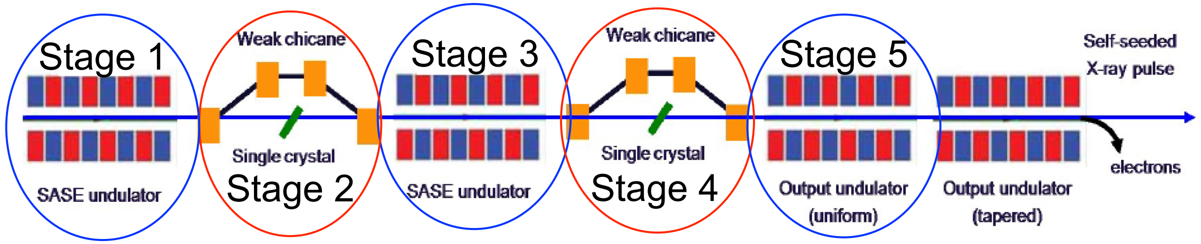


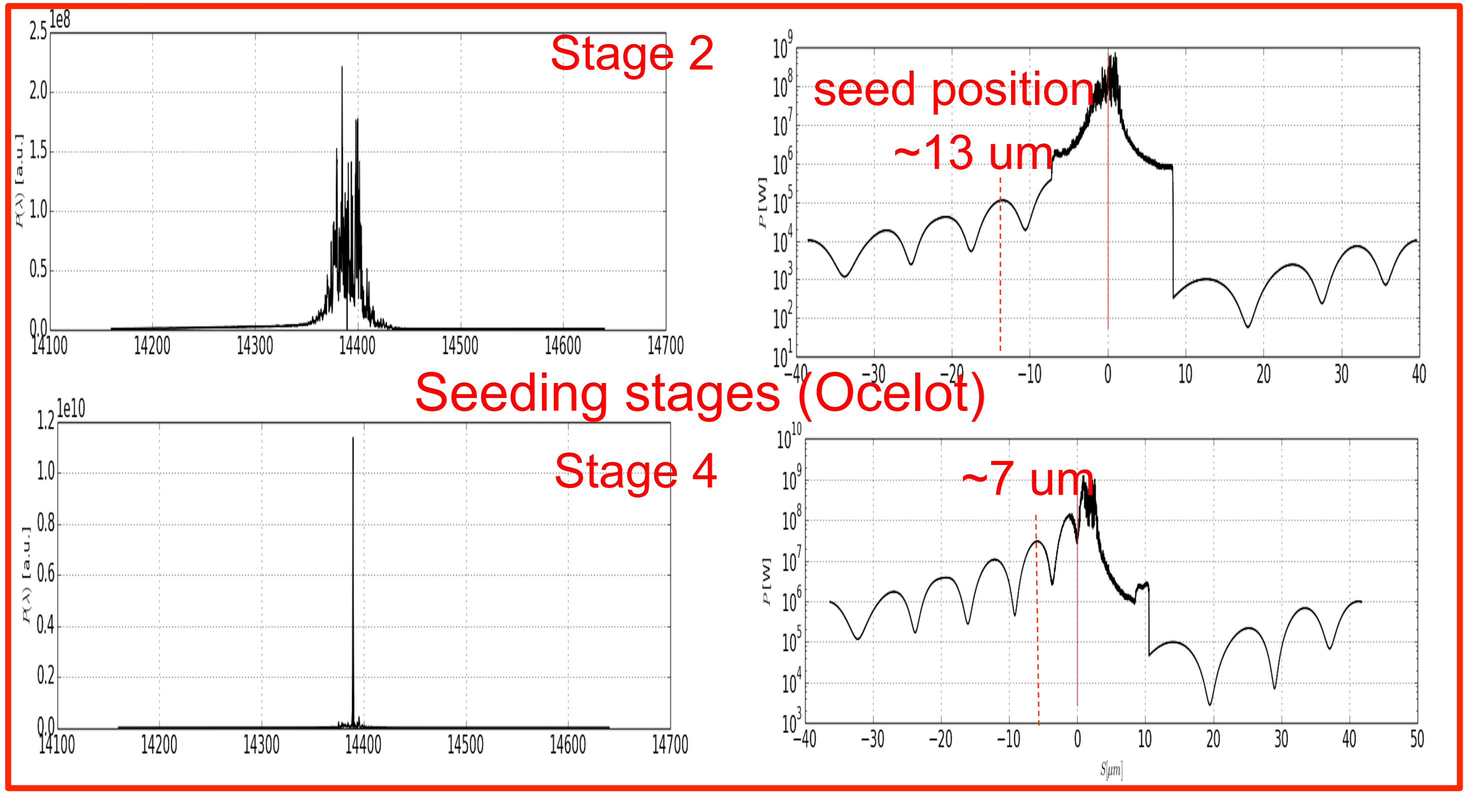


- The S-band Transverse Deflecting Structure (TDS) after BC2 is used for long. PS measurements
- Measurements are performed in BC2 dump with large vertical dispersion optics (σ_y/D_y=1.97e-5)
- TDS **time resolution** of **14 fs** reached for 250 pC, not small enough for 100 pC measurement
- Measurements for 100 pC will be performed in the future with optimized optics

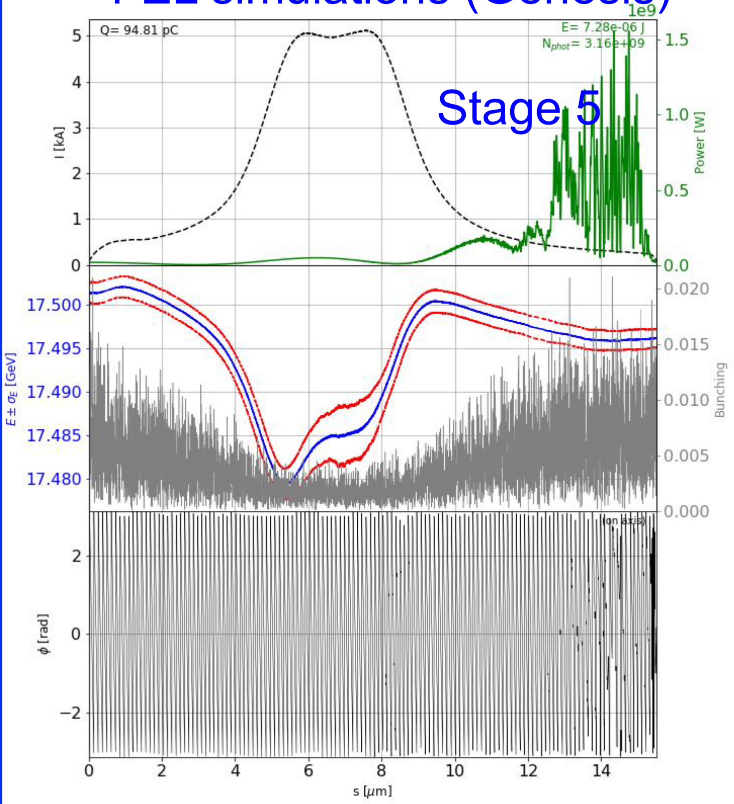
HXRSS Simulation procedures

- What is the highest reasonable photon energy for HXRSS?
- How many undulator segments should be reserved for 1st and 3rd stage?

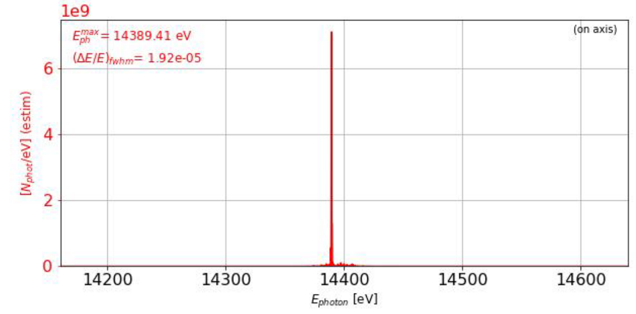




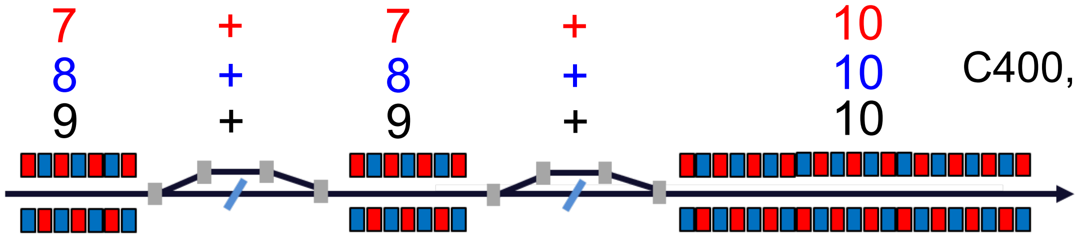
FEL simulations (Genesis)



17.5GeV, 14.4keV, C400, 100 µm diamond

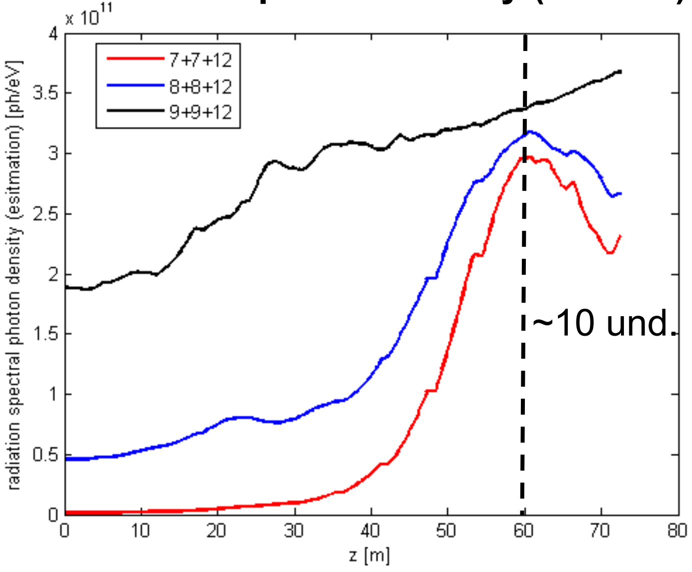


17.5GeV, 14.4keV case, stage 5

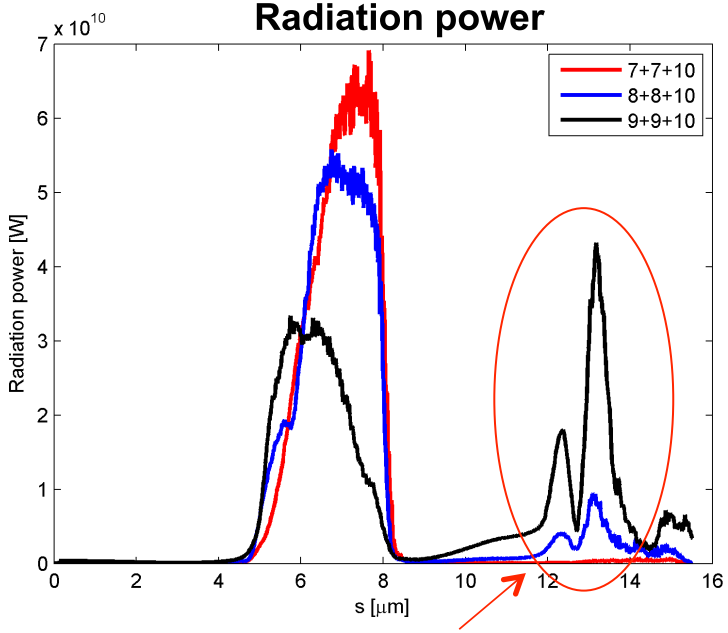


C400, 100 μm diamond

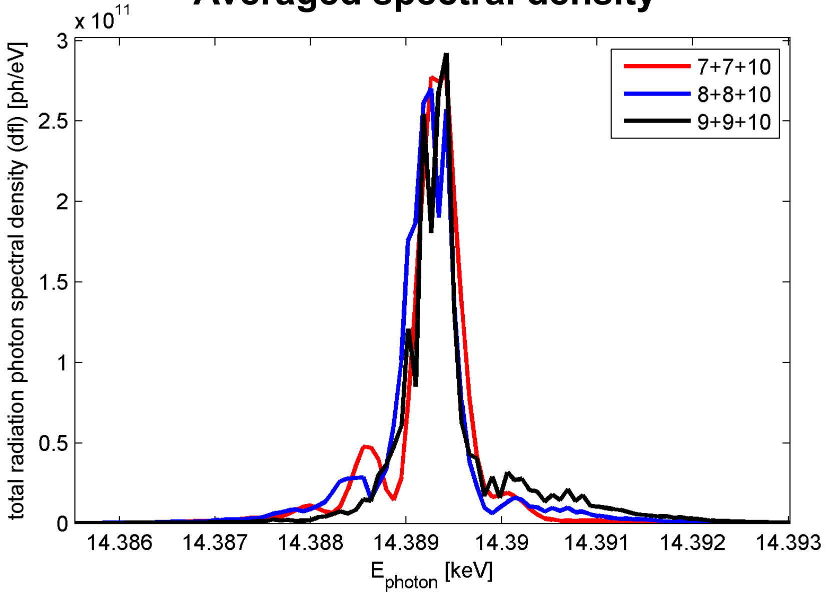
Maximum spectral density (on-axis)



Radiation power



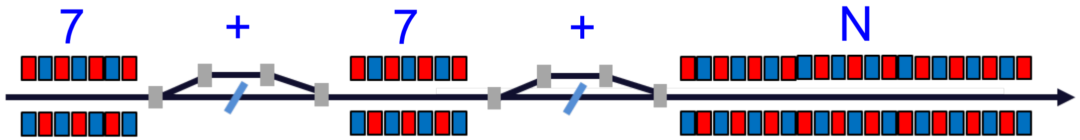
Averaged spectral density



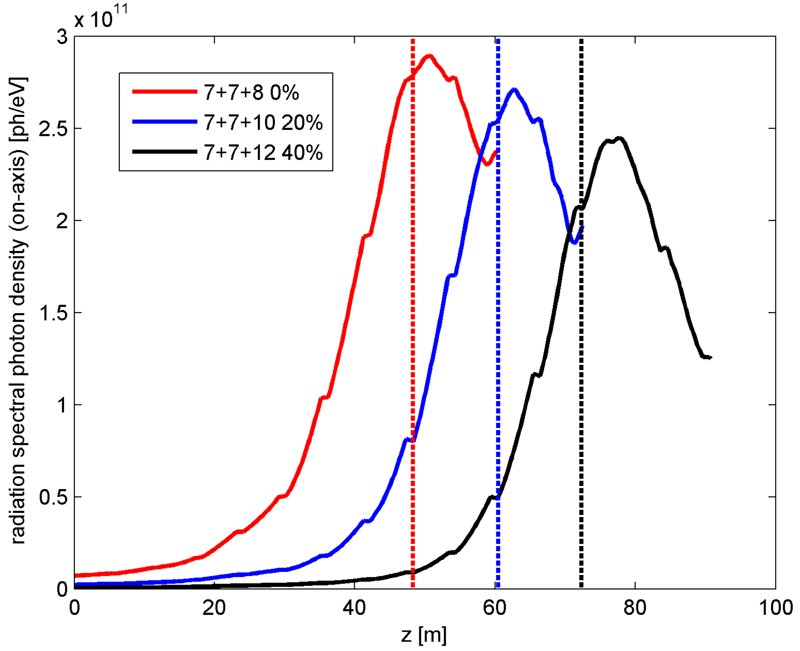
- 9+9 case has a strong pre-pulse amplified from stage 3
- 7+7 has the highest radiation power
- Max. spectral density is comparable in these 3 cases

7+7 would be the best choice since it is the cleanest and has no pre-pulse!

Emittance tolerance (7+7)

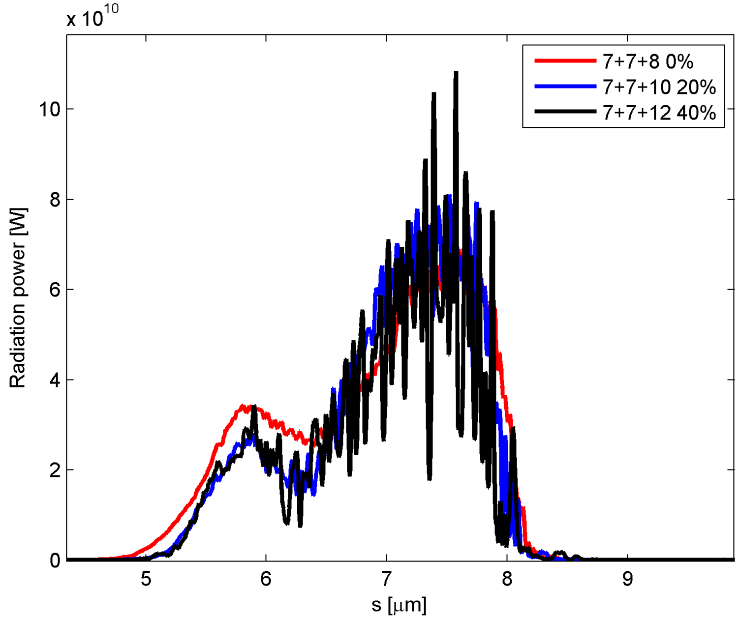


Maximum spectral density (on-axis)

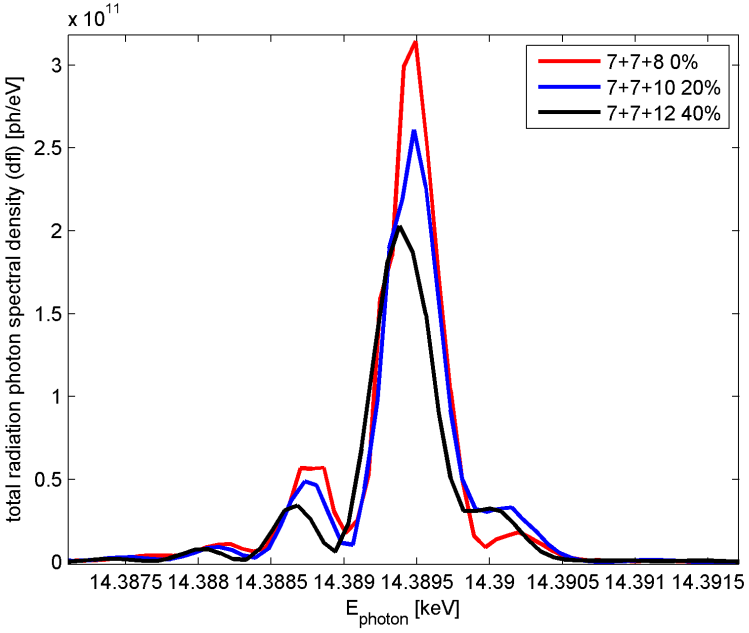


Dashed lines shows the position taken for other two plots

Radiation power

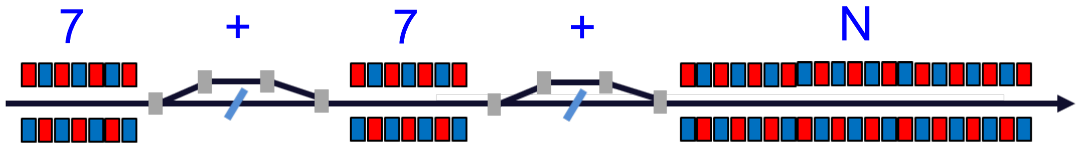


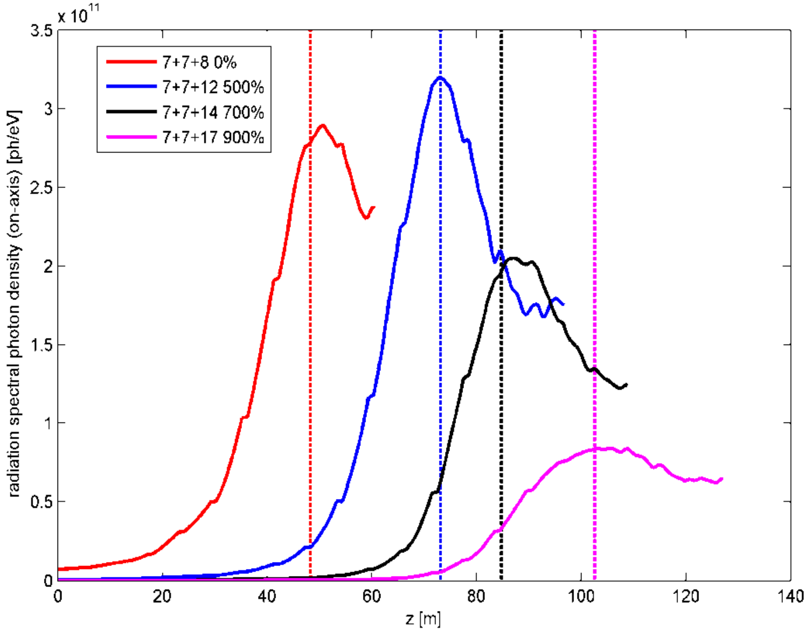
Averaged spectral density

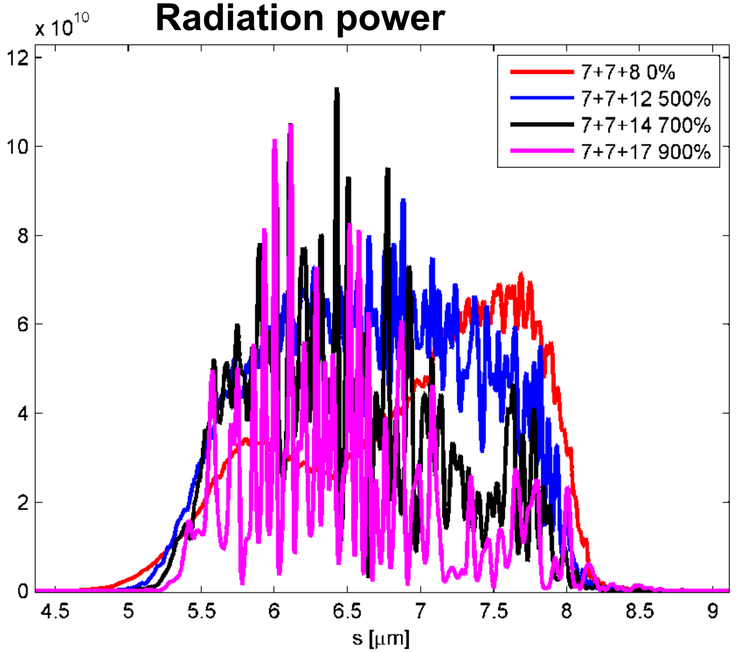


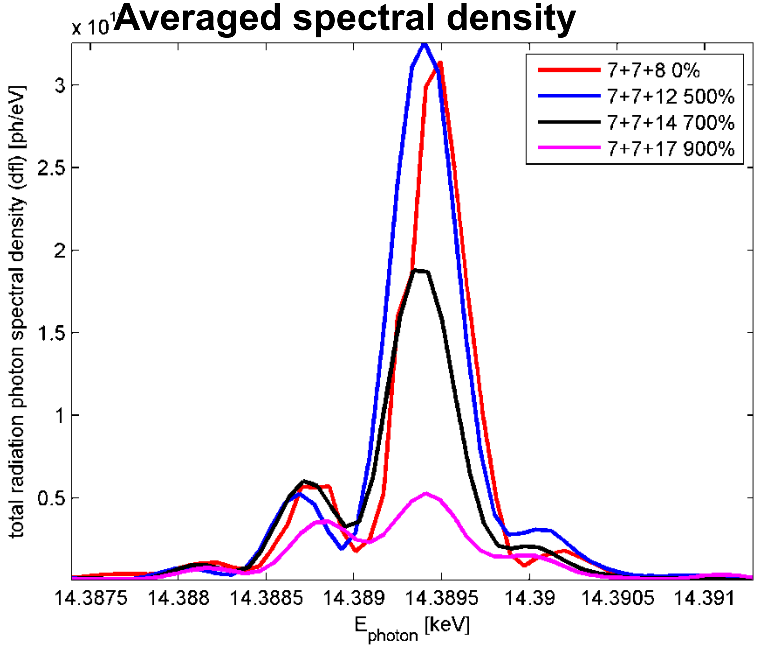
- No big change with 40% increase of emittance for 7+7+ N (N is near the saturation point)

Energy spread tolerance (7+7)







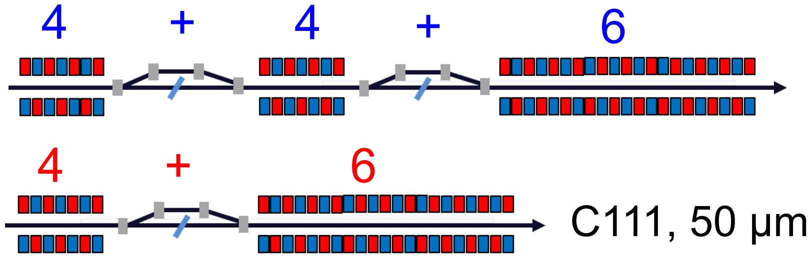


Dashed lines shows the position taken for other two plots

- No big change with 500% increase of energy spread for 7+7+N (N is near the saturation point)

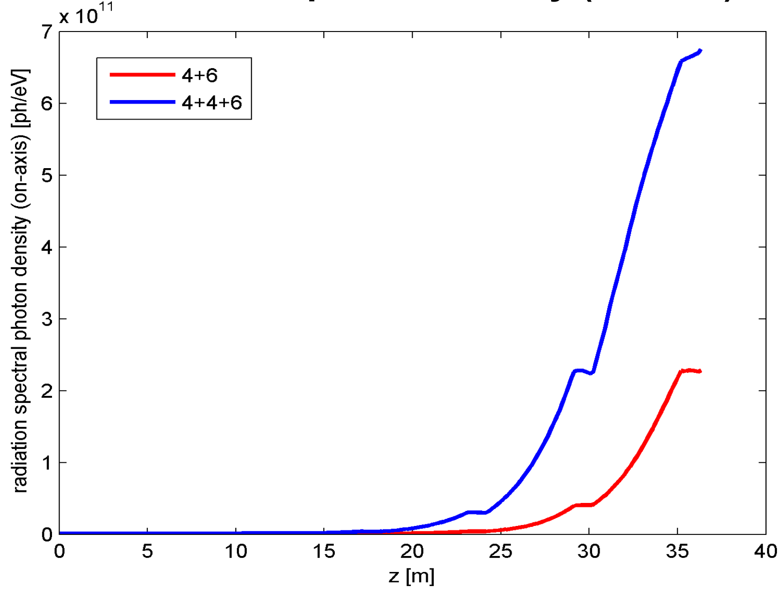
7+7 is enough for 14.4 keV case, **8+8 is chosen** to further increase the tolerance.

8 GeV, 3.5 keV case: comparison 4+4+6 VS 4+6

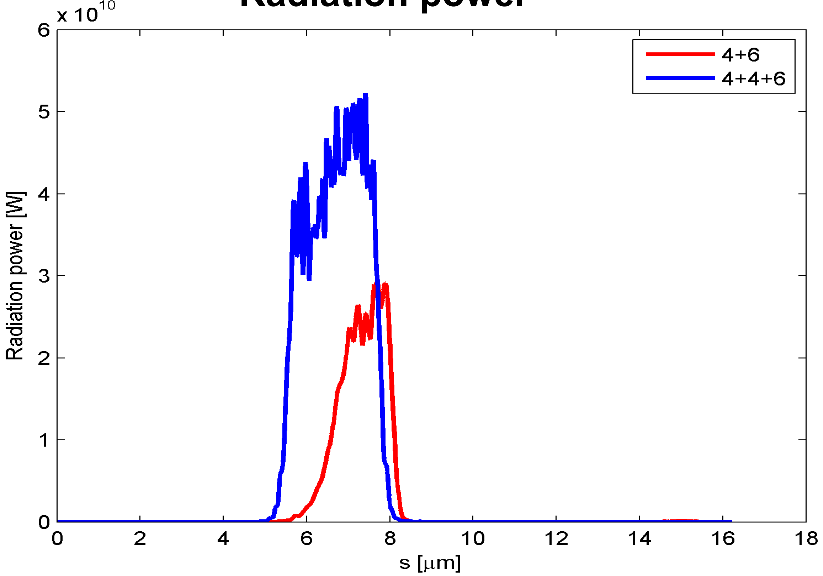


C111, 50 μm diamond

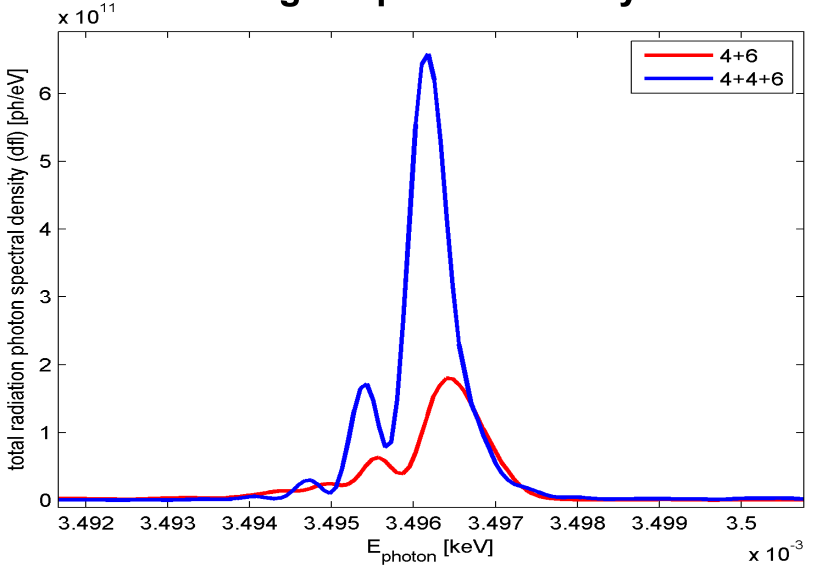
Maximum spectral density (on-axis)



Radiation power

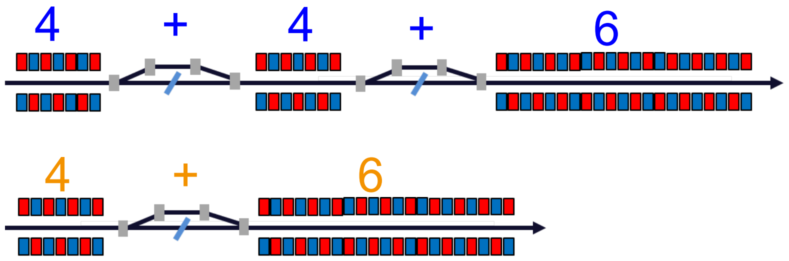


Averaged spectral density



- Heat-loading from seeded signals can be tackled with special 2-chicane design
- Heat load: max. 2.2 uJ incident power at stage 4-> 90% deposition at 3.5 keV-> **max. 2 uJ deposited**
- At the second crystal, almost Fourier limited -> S/N gain: BW ratio SASE/seeded ~10

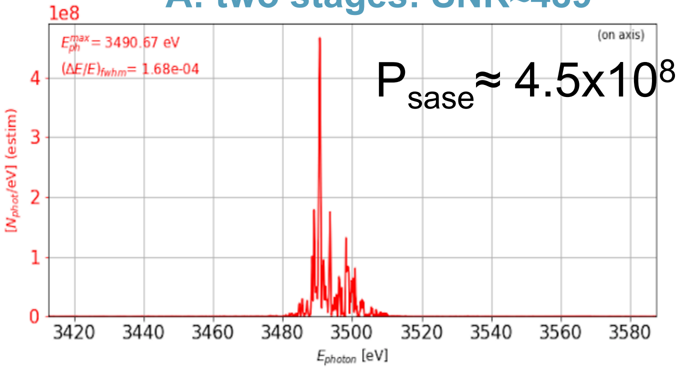
8 GeV, 3.5 keV case: SNR comparison



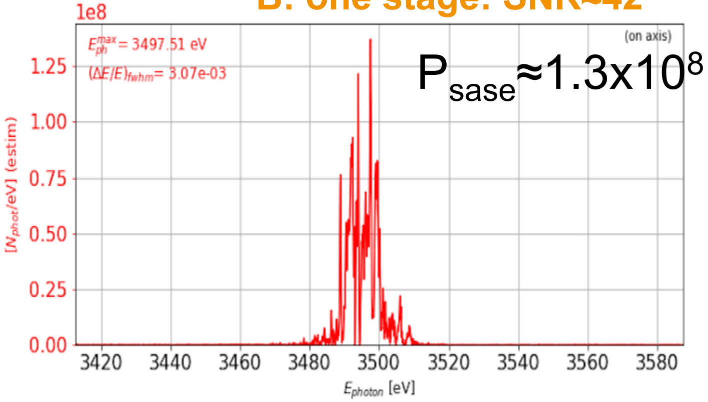
- Signal to noise ratio (SNR) definition:
- Peak spectral density with HXRSS at the last stage: P_{seeded}
- Peak spectral density w/o HXRSS (only SASE) at the last stage: P_{sase}

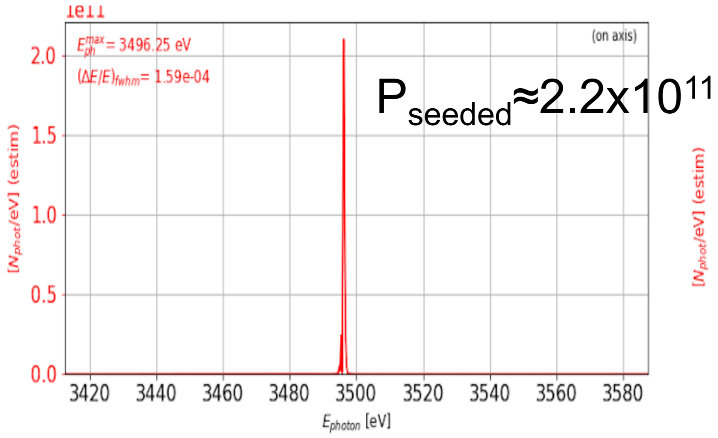
$$SNR=P_{seeded}/P_{sase}$$

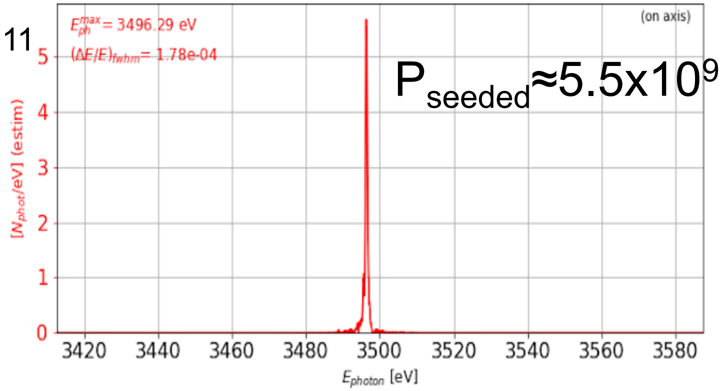
A: two stages: SNR≈489

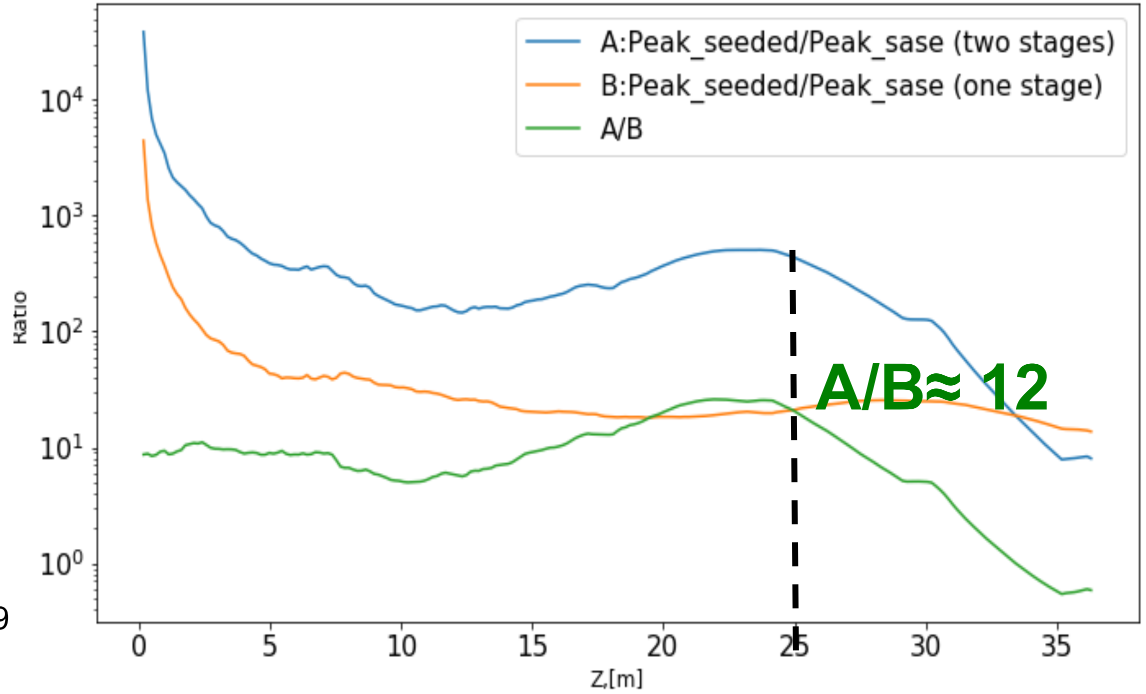


B: one stage: SNR≈42



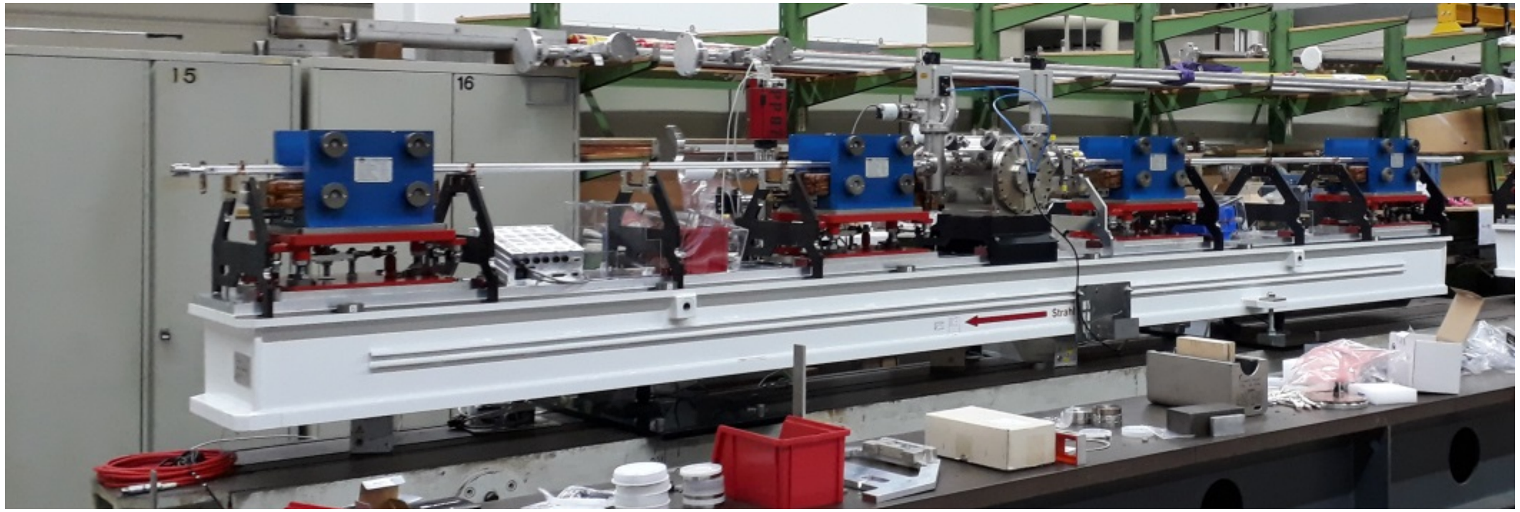


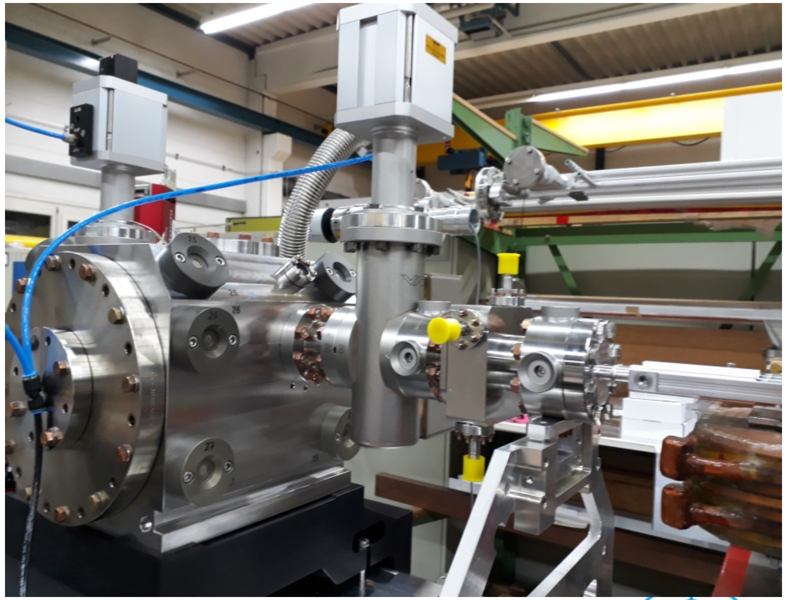




Schedule for HXRSS implementation and commissioning

- SASE2: first e-beam in **March 2018**, first lasing in **May 2018**
- SASE2 chicanes, girders and monochromator chambers are assembled
- Monochromators will be ready by the end of 2018
- Self-seeding **chicane installation** in SASE2: **December 2018**
- Self-seeding chicane construction for **SASE1 (2018-2019)**





Summary and Prospects

- **Long. PS optimized** for **100 pC case** for HXRSS with S2E simulations
  - **Fast tracking simulations** can be performed in the future using **Ocelot** or **X-track** (talk by M. Dohlus THA1WA01)
  - **Experimental demonstration** of optimized long. PS **is critical** for HXRSS, **will be performed** with optimized TDS optics
- **HXRSS simulations** have been perforemed for **3.5-14.4 keV** range
- **Chicane location** chosen based on simulations for 14.4 keV case, which requires longer undulators
- Emittance and energy spread tolerance studied for 7+7 case
- 7+7 is enough for 14.4 keV case, **8+8 is chosen** to further increase the tolerance
  - For **higher than 14.4 keV**, **2nd or higher harmonic bunching** can be used by tuning part of the radiator to a harmonic of the fundamental
  - **Tapering study** is underway to further improve HXRSS performance

Thank you for your attention!

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