Layout of the HHG seeding experiment at FLASH

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T. Laarmann T. Maltezopoulos, V. Miltchev, M. Mittenzwey,
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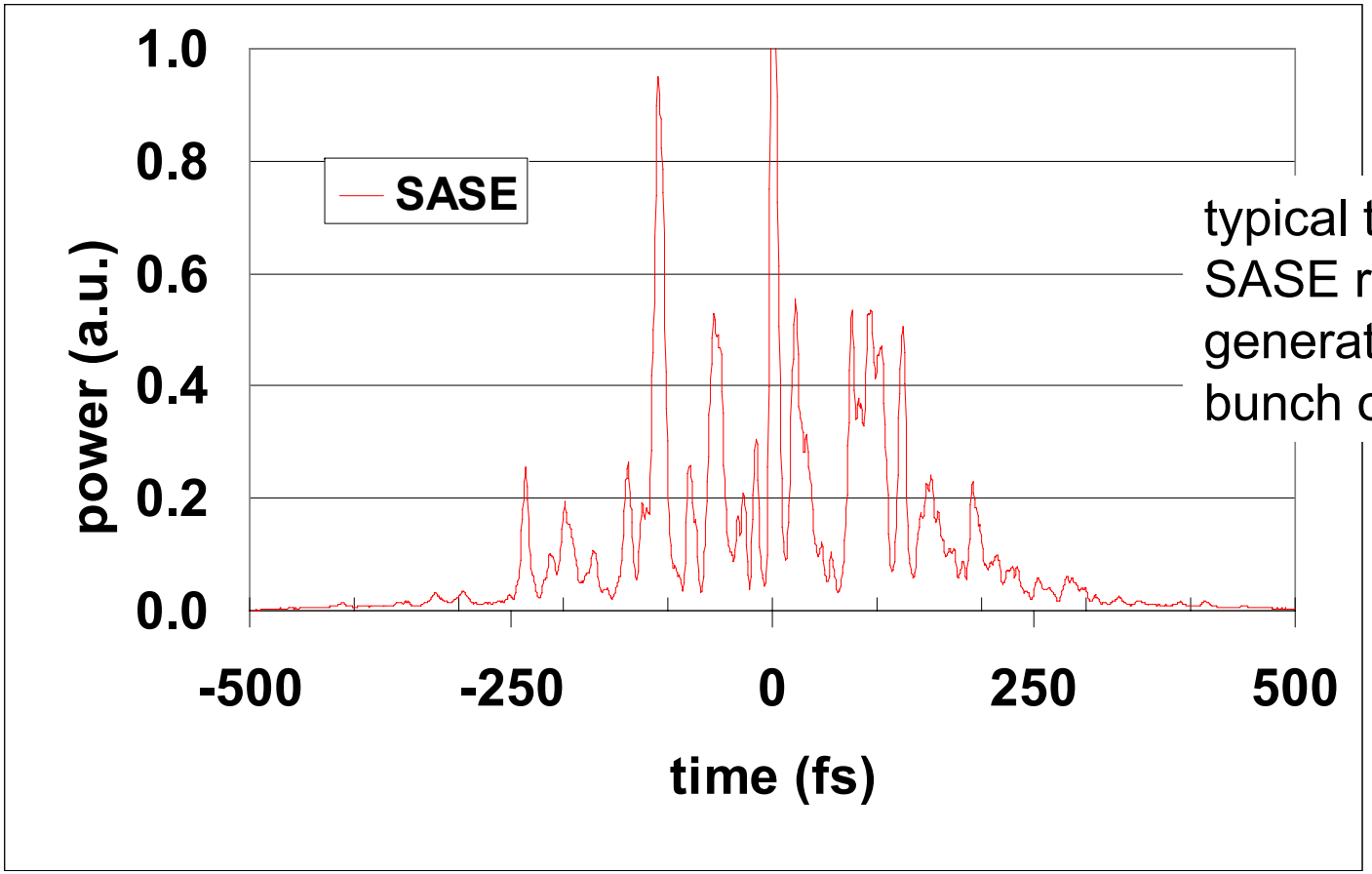
Motivation



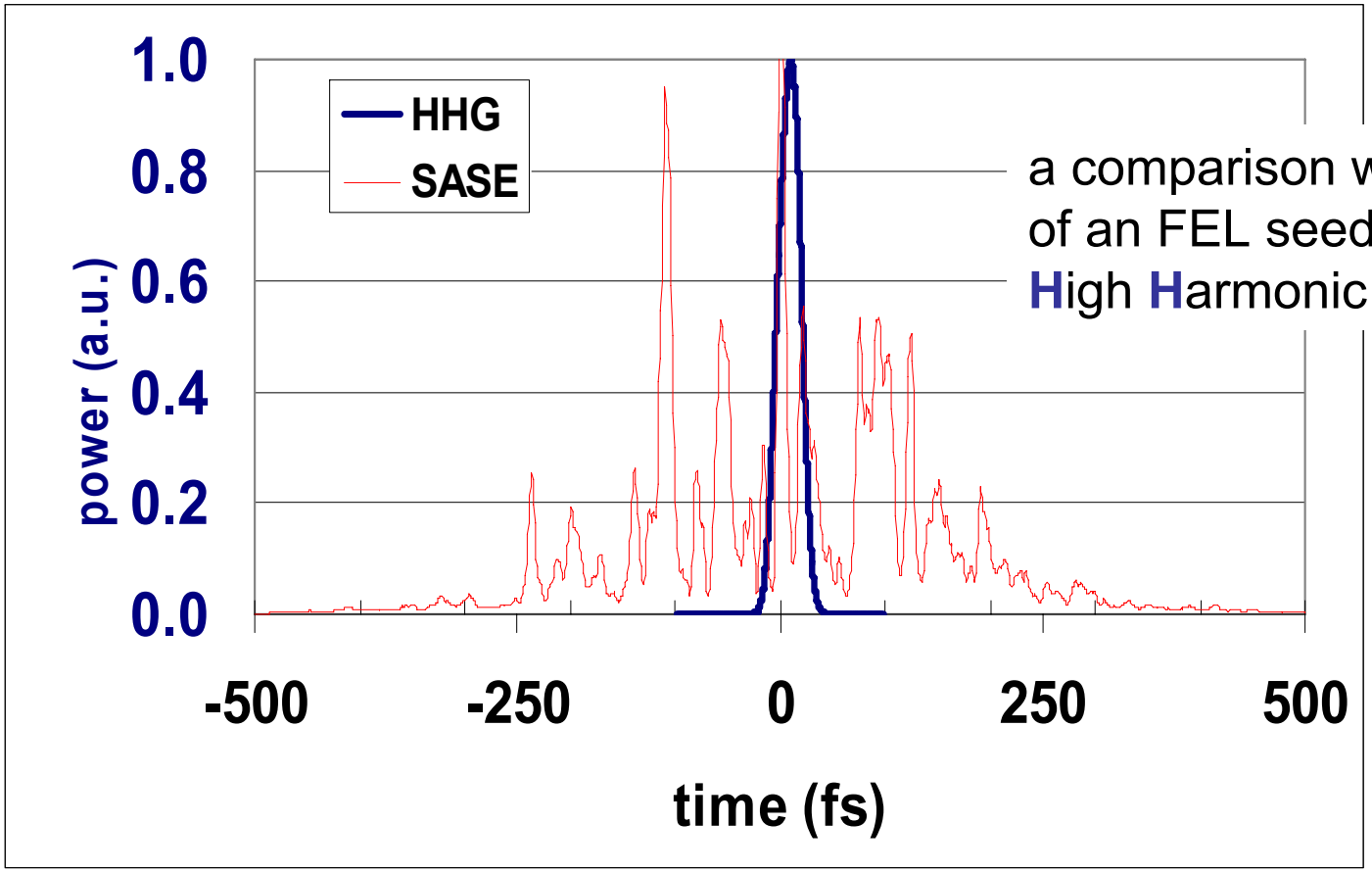
typical temporal profile of a SASE radiation pulse, generated by an electron bunch of $\sigma_t \approx 250$ fs

Due to the start up from noise:

$\Rightarrow$ shot-to-shot fluctuations of the pulse energy

$\Rightarrow$ the output consists of a number of uncorrelated spikes (poor temporal coherence)

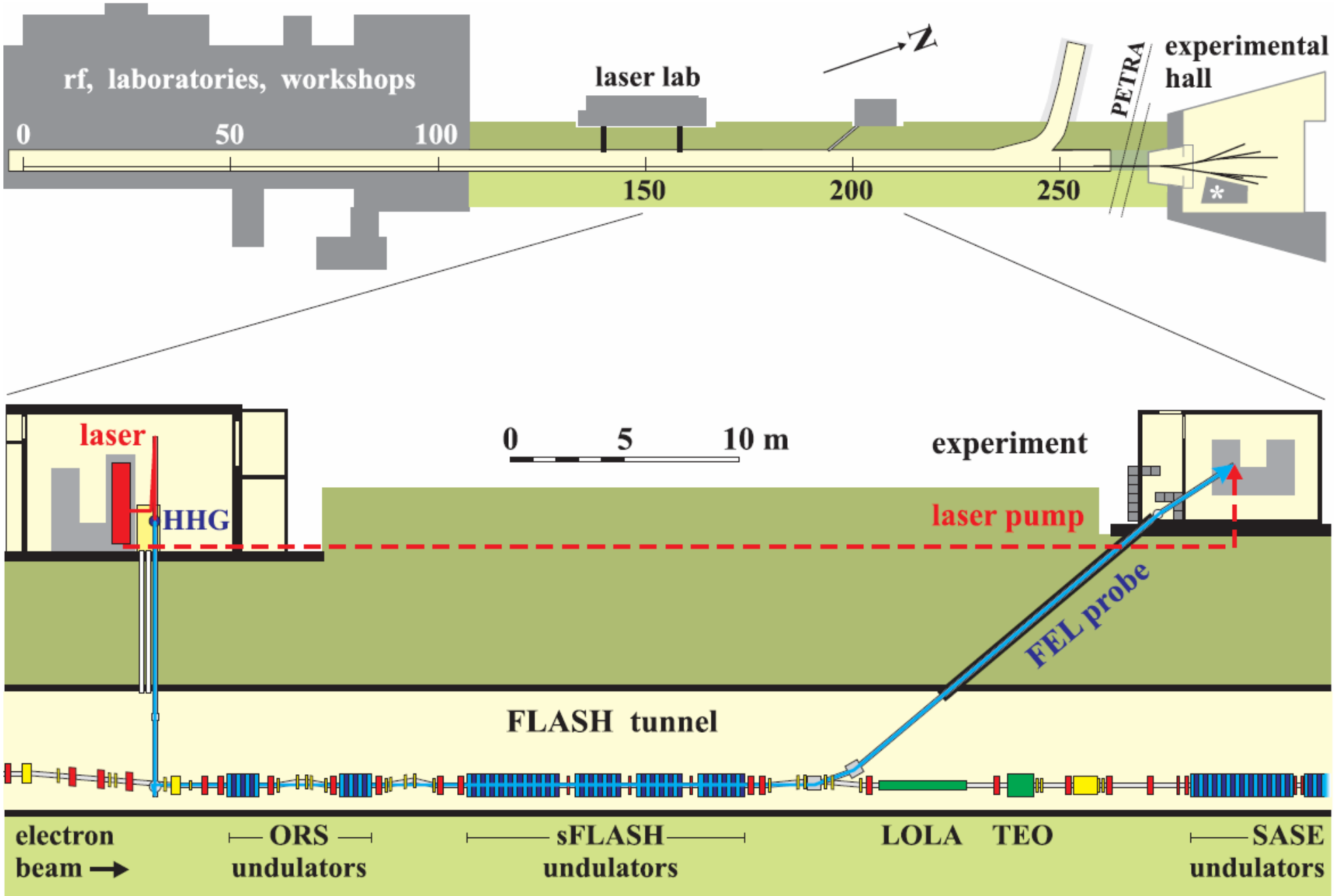
Motivation



a comparison with the output of an FEL seeded using **H**igh **H**armonic **G**eneration (**HHG**)

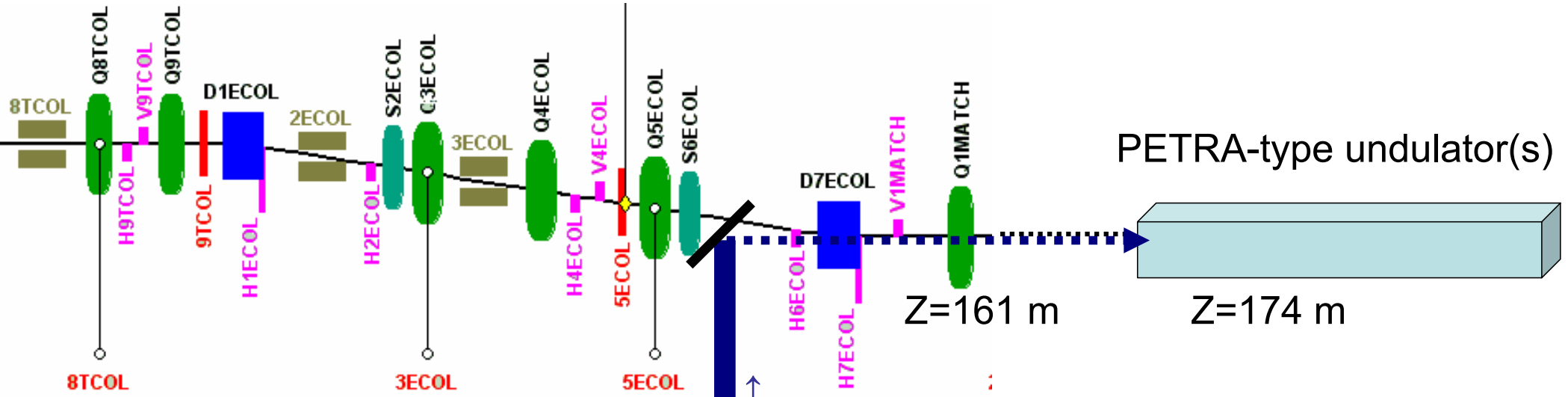
⇒ high shot-to-shot stability and high peak power (**GW level**)
⇒ generation of fully coherent pulses of variable length (**20–40 fs FWHM**)
⇒ wavelength range ~**13-30 nm**
⇒ reduction of saturation length
⇒ HHG runs in '**parasitic' mode**, i.e. parallel to the normal SASE operation
⇒ pump probe experiments with fs synchronization

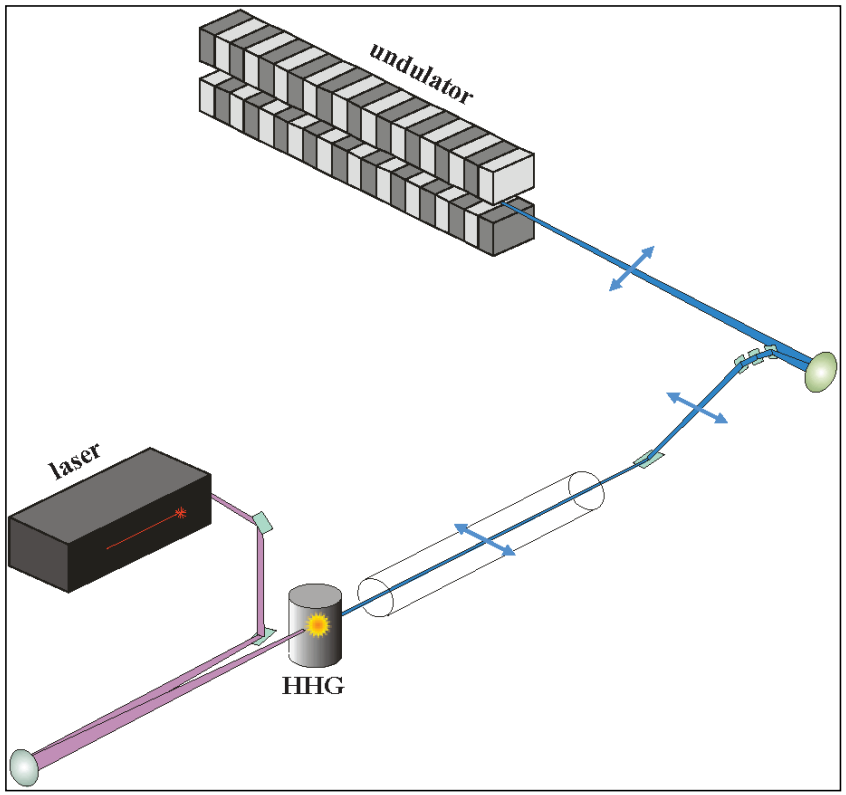
sFLASH schematic set up



S. Khan et. al. "sFLASH: AN EXPERIMENT FOR SEEDING VUV RADIATION AT FLASH", FEL'08

sFLASH schematic set up





30 nm seed

gas cell (e.g. Ar)

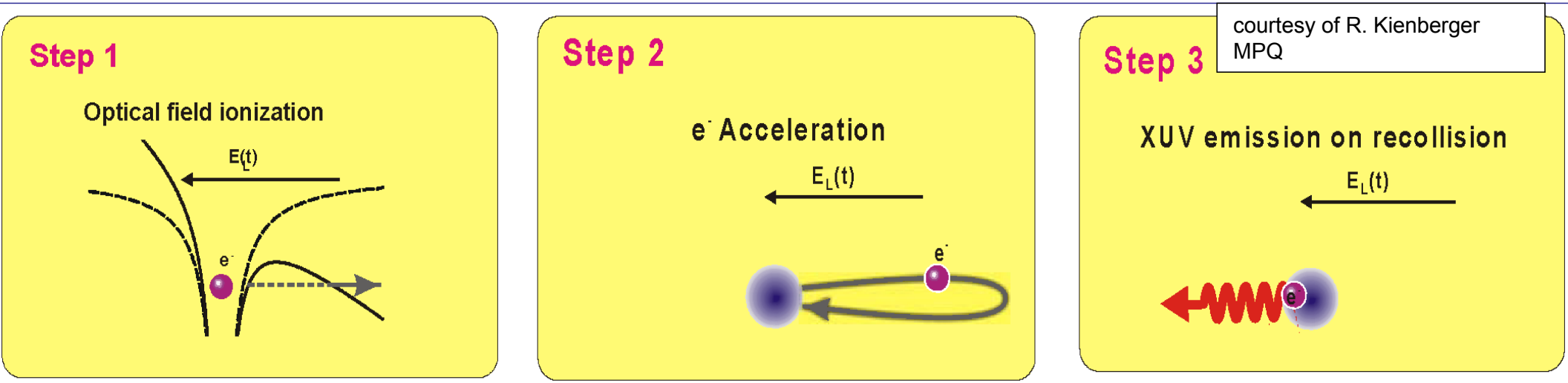
800 nm, 20mJ, 35 fs

Ti:SA laser

to pump-probe

simultaneous generation of odd harmonics of the fundamental 800 nm.
n=1,3...27...

Properties of the HHG radiation



courtesy of R. Kienberger
MPQ

• The interaction between the intense laser pulse with rare gas atoms results in the generation of higher-odd harmonics of the driving laser frequency (HHG)

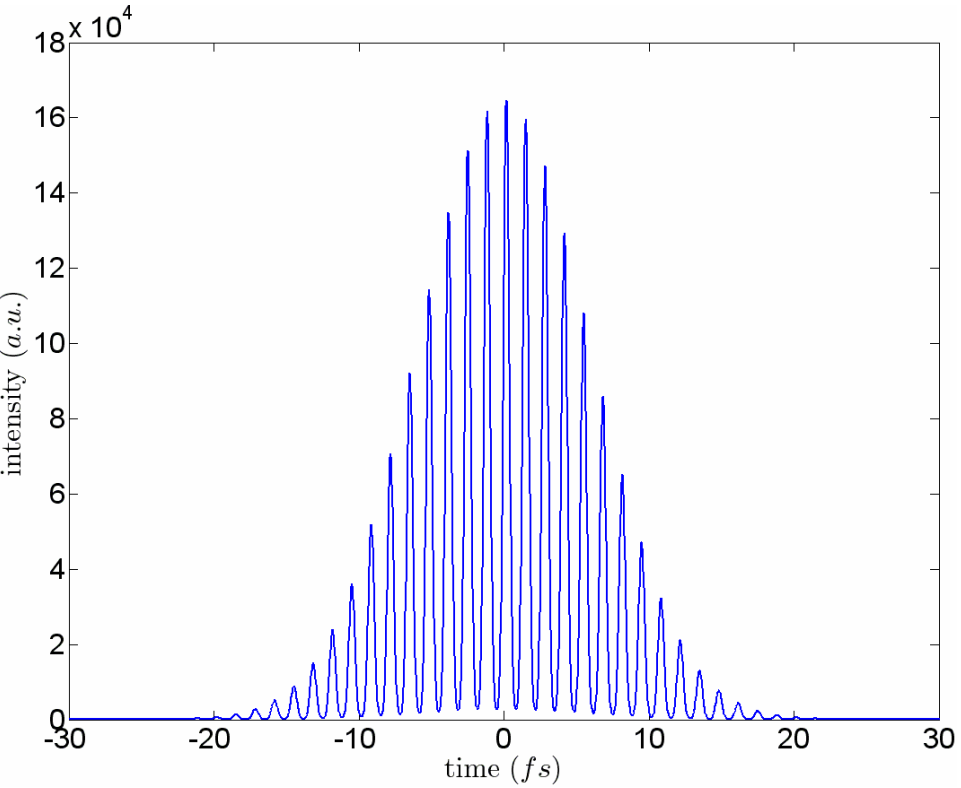
Semi-classical three step model [1,2]:

1. Close to the peak of the laser electric field, electron tunnels through the potential barrier formed by the combined Coulomb and laser fields
2. It oscillates almost freely in the laser field, gaining kinetic energy
3. The energy gained is converted into a high-energy photon through recombination with the parent ion

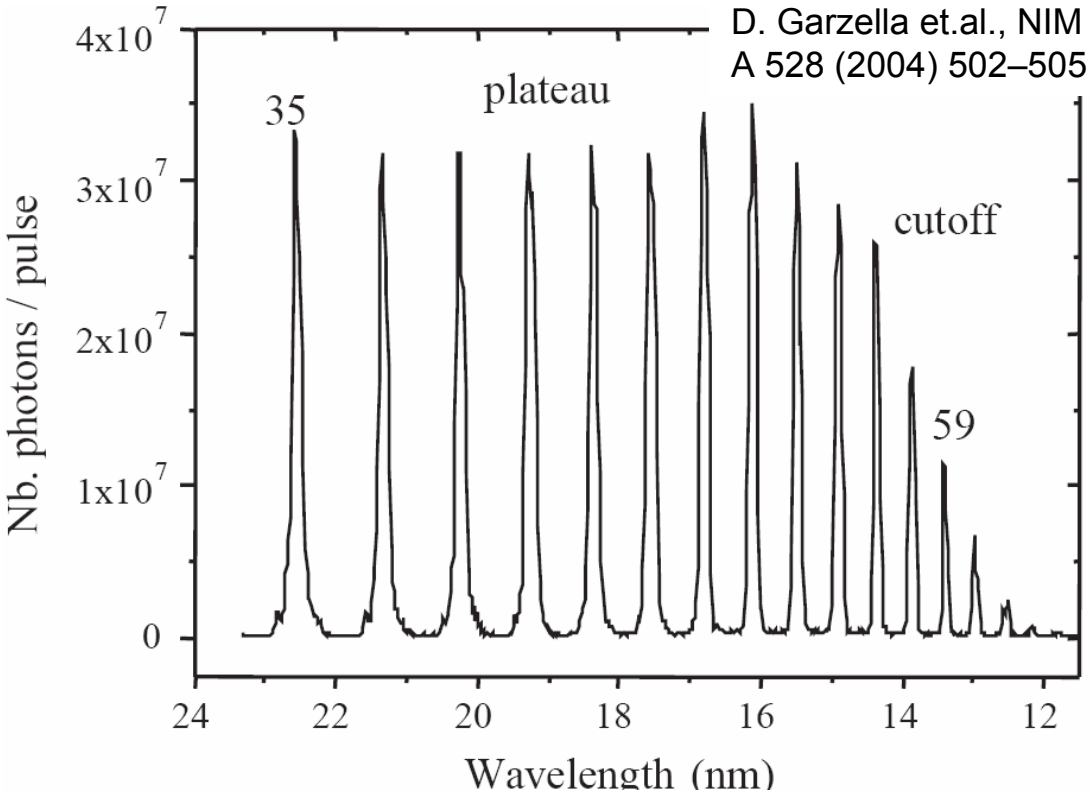
1. P. B. Corkum, Phys. Rev. Lett. 71, 1994 (1993).
2. K. J. Schafer, et.al., Phys. Rev. Lett. 70, 1599 (1993).

Properties of the HHG radiation

- The interaction between the intense laser pulse with rare gas atoms results in the generation of higher-odd harmonics of the driving laser frequency (HHG)
- The HHG radiation forms '*combs*' in frequency and time domains, resulting in atto-second pulse structures separated by half driving laser period

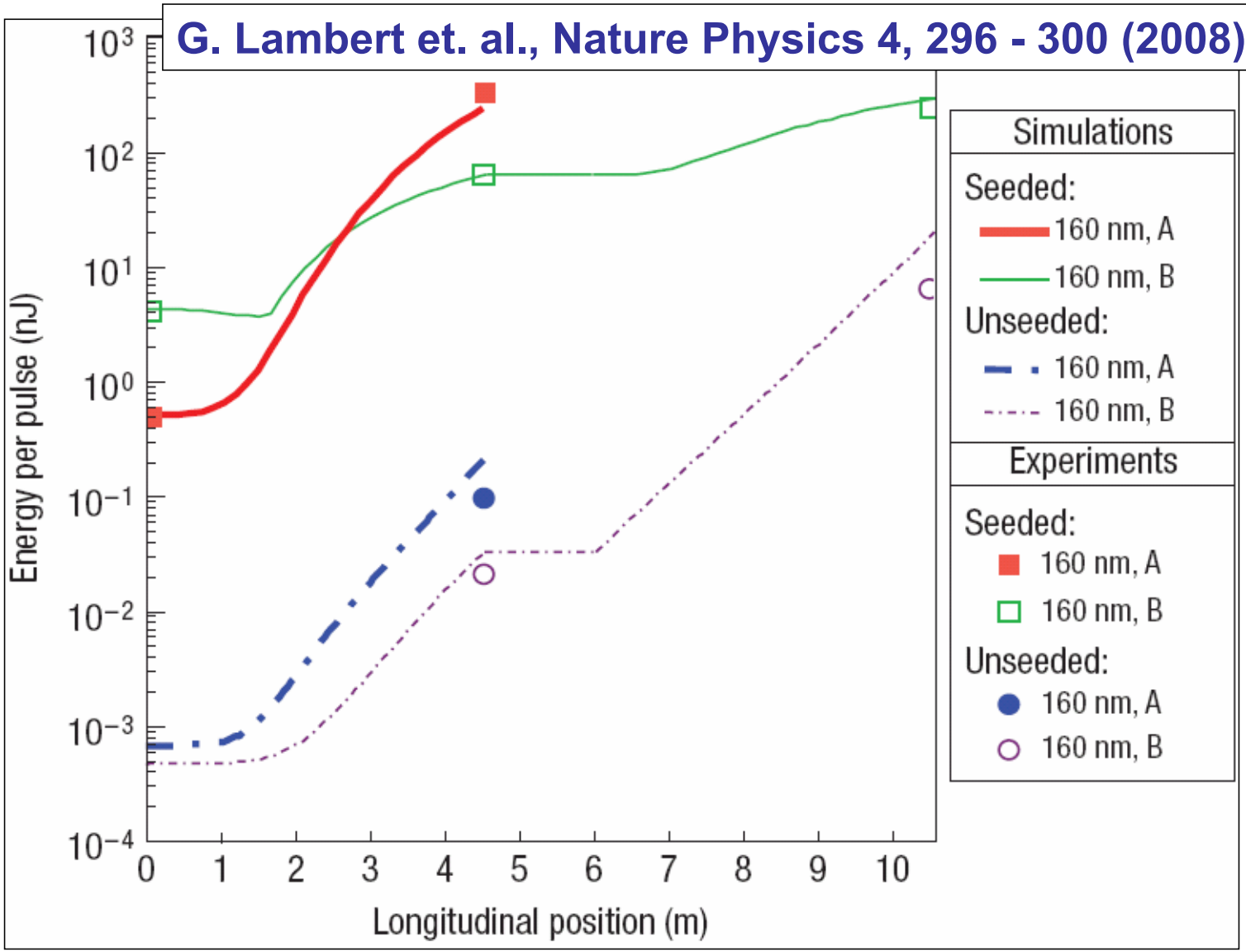


simulated time profile of the seeding HHG pulse



typical spectrum measured in Ne. Seeding with superimposed harmonics possible provided that $1/n > \rho$

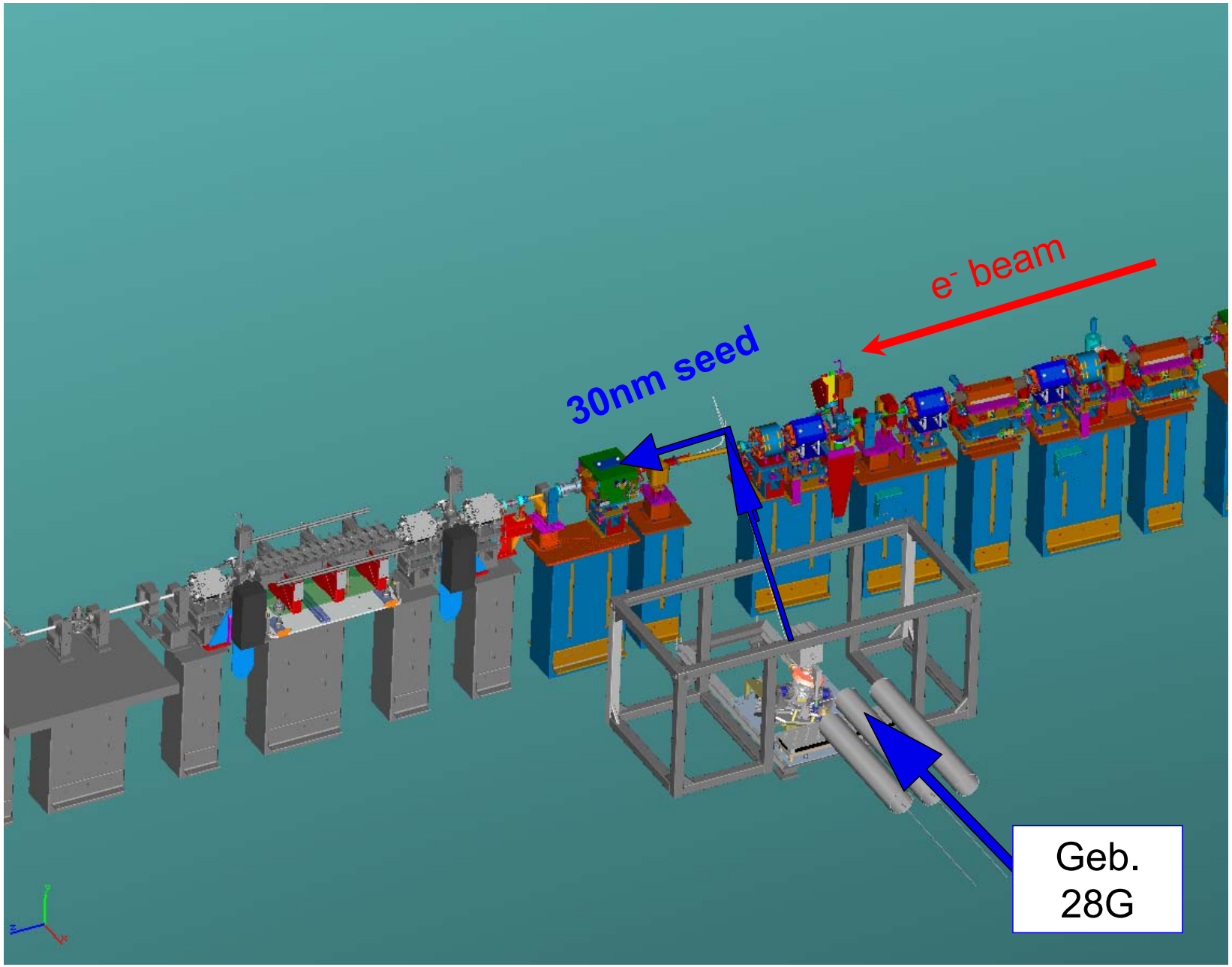
HHG seeding - proof of principle experiments



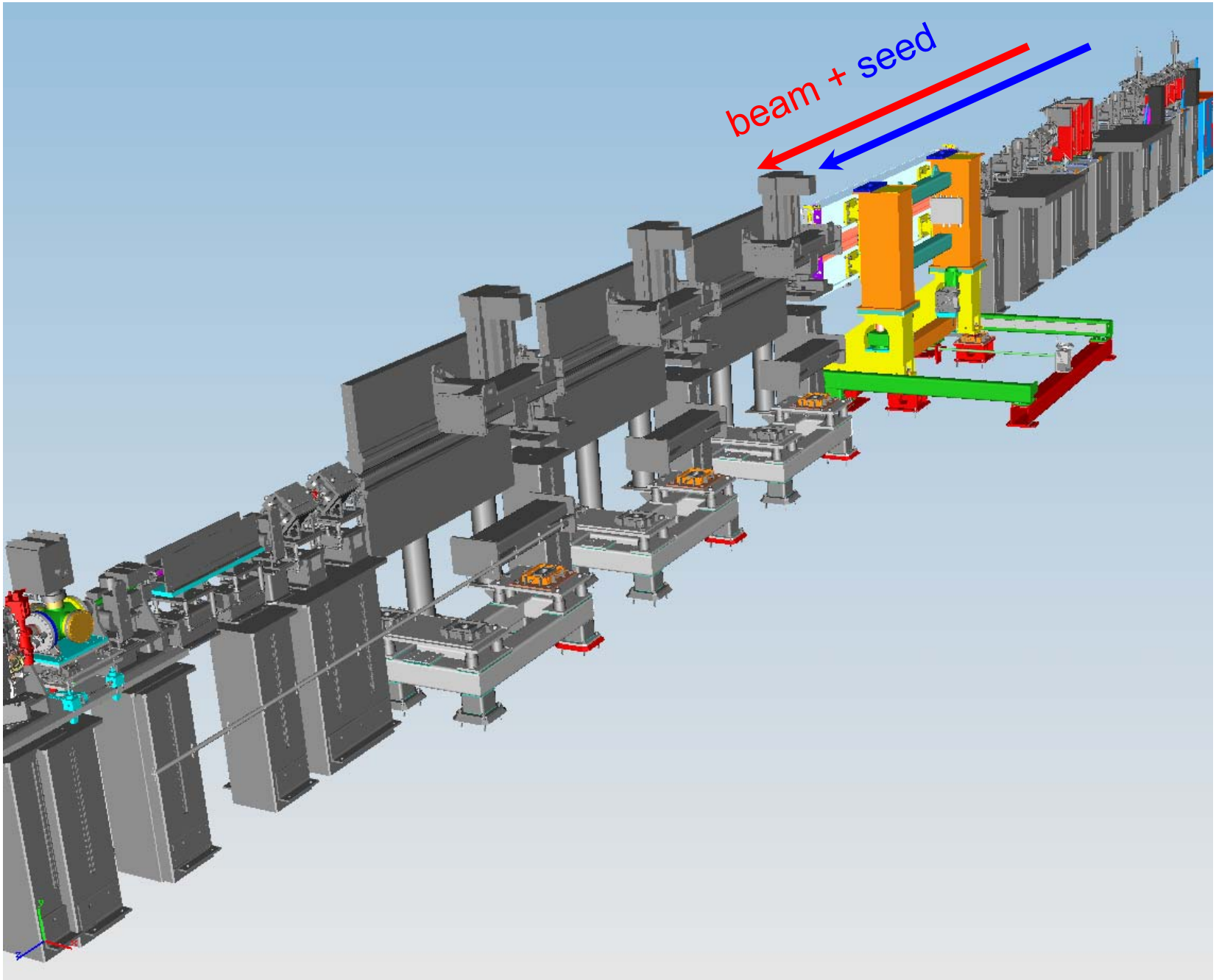
An experiment in SPring-8 Compact SASE Source has demonstrated HHG seeding at 160 nm.

Evolution of the 160 nm FEL pulse energy along the undulator for two different seed pulse energies.

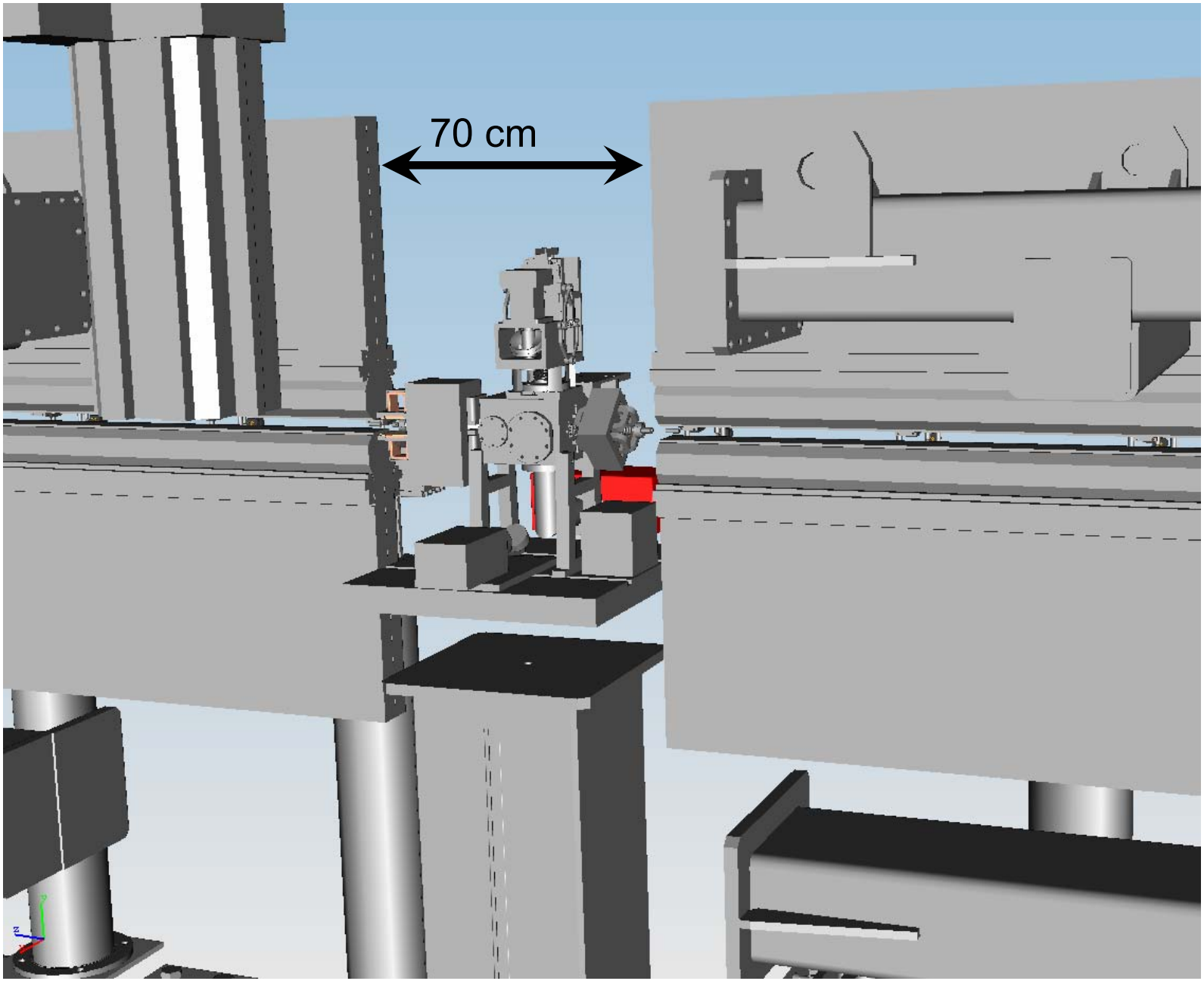
HHG in-coupling



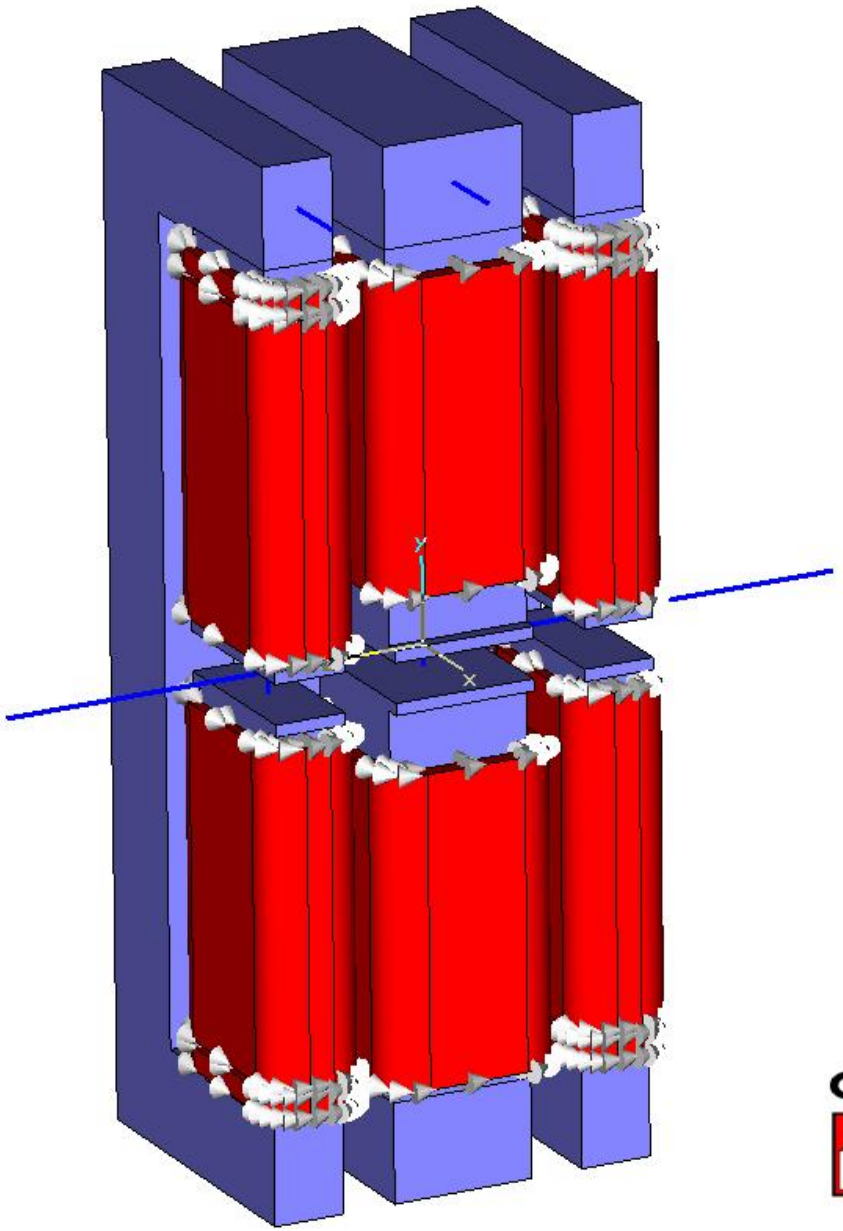
Seeding section



Undulator intersection



Phase shifter

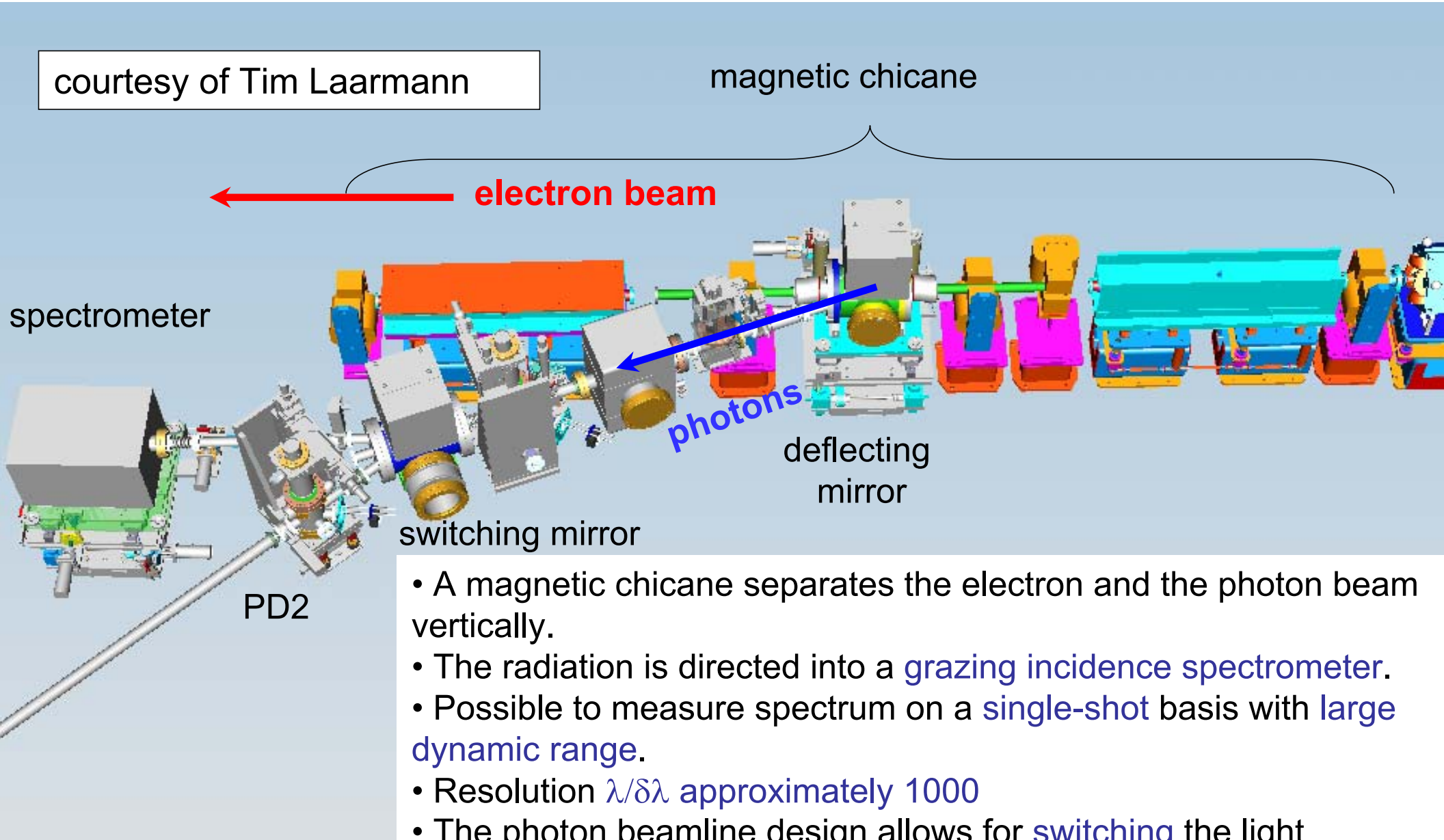


- Electromagnetic, low coercivity (<11A/m) iron, design by Efremov Institute, St. Petersburg
- One common PS used for all three **main coils**
- Additional small **corrector coils** (separate PS) are built-in.

CST

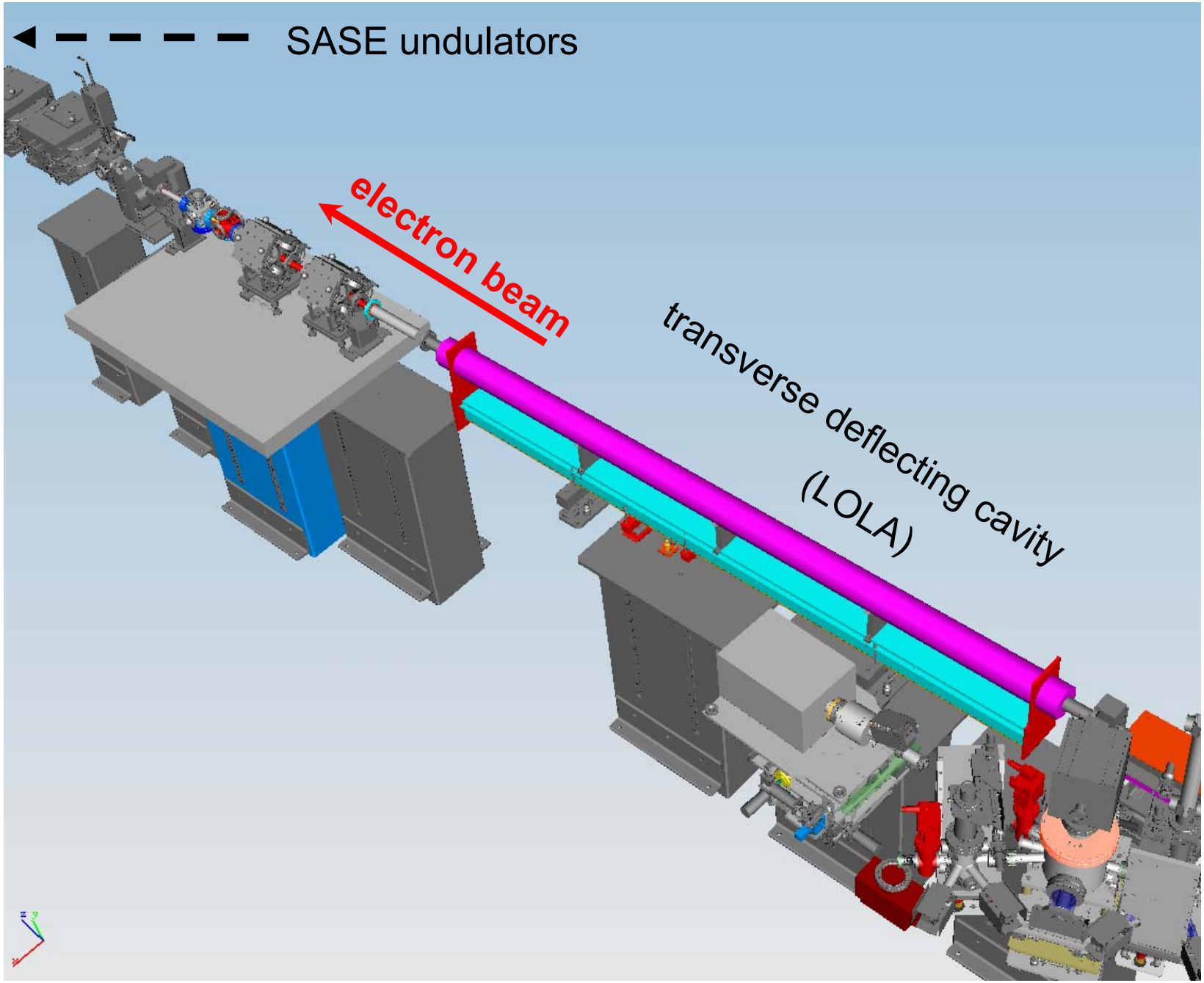
Layout of the sFLASH photon beamline

courtesy of Tim Laarmann

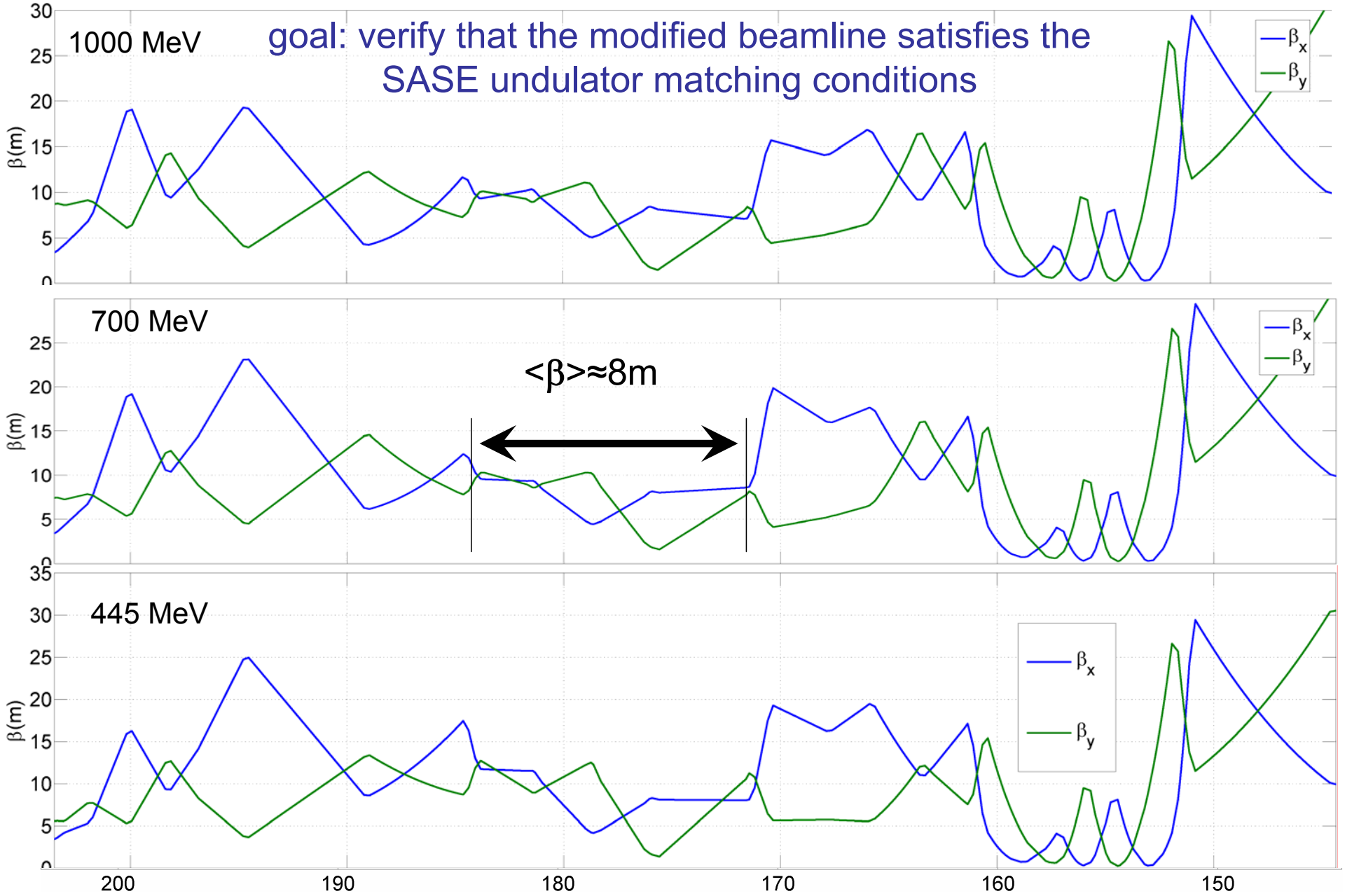


- A magnetic chicane separates the electron and the photon beam vertically.
- The radiation is directed into a grazing incidence spectrometer.
- Possible to measure spectrum on a single-shot basis with large dynamic range.
- Resolution $\lambda/\delta\lambda$ approximately 1000
- The photon beamline design allows for switching the light between the spectrometer branch and the experimental hutch

Matching to SASE undulators



Optics at different energies

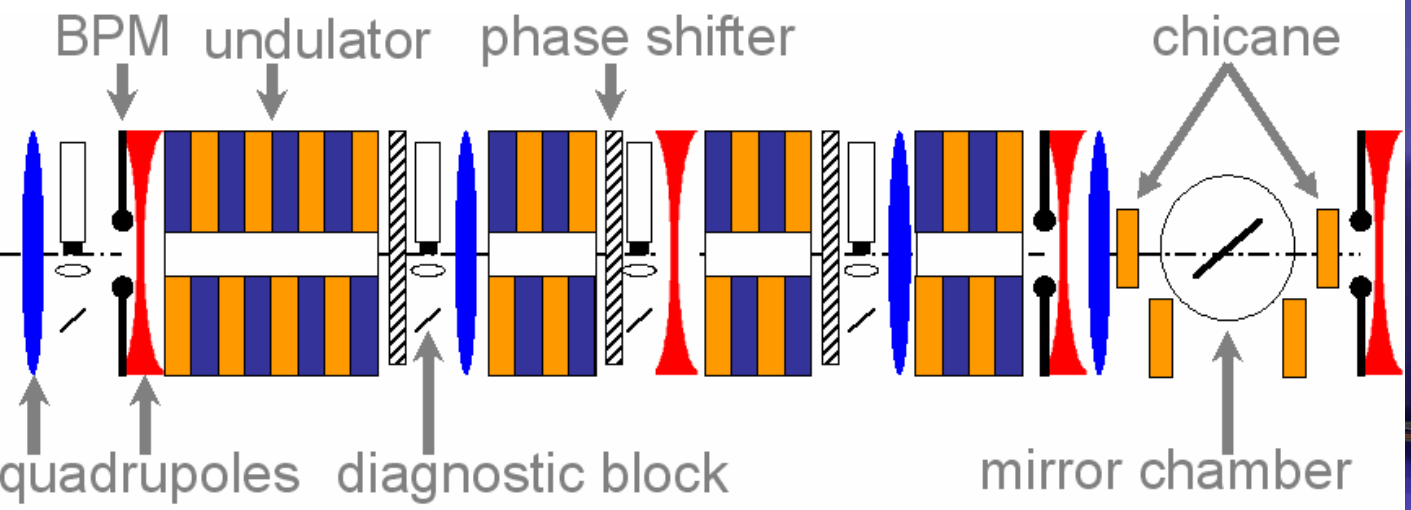


Beamline modifications summary

Modifications apply to the section between the collimator and SASE undulators

- additional hardware to be installed
  - four HHG undulators: 1x4(m) and 3x2(m)
  - phase shifters, additional steerers
  - mirror chamber to separate HHG radiation and electron beam
  - diagnostics
  - LOLA/screen (due to installation of ACC7 in future)
- ORS+chicane to be moved upstream $\Rightarrow$HHG undulators closer to input window
- 10(mm) beam pipe in HHG undulator section. Vacuum chamber 15x7.7 mm
- Some quadrupoles should be moved $\Rightarrow$different optics is required
- Compatibility between SASE operation, HHG, ORS, LOLA is required
- Assure full transmission with no losses

Beamline modifications summary



Undulator U32, 31.4mm period, 2m length

- Four planar variable-gap undulators of 10m total length, separated by 70cm intersections.
- Undulators of the same type as those installed in the PETRA synchrotron radiation source
- Undulator period of 31.4mm and 33mm.
- Undulator vacuum chamber with a vertical size of 7.7mm.
- Transverse focussing, accomplished by movable quadrupoles placed in-between the undulator segments, average beta-function of the order of 8m.
- Electron beam diagnostics realized using wire scanners, optical transition radiation (OTR) and Ce:YAG screens and beam position monitors
- Wire scanners and screen stations compacted in a common diagnostic block, usable for both electron beam and HHG radiation diagnostics.

Requirements to HHG seed

- **spatial overlap** between electron bunch and HHG pulse

$\Rightarrow$ good pointing stability of optical laser

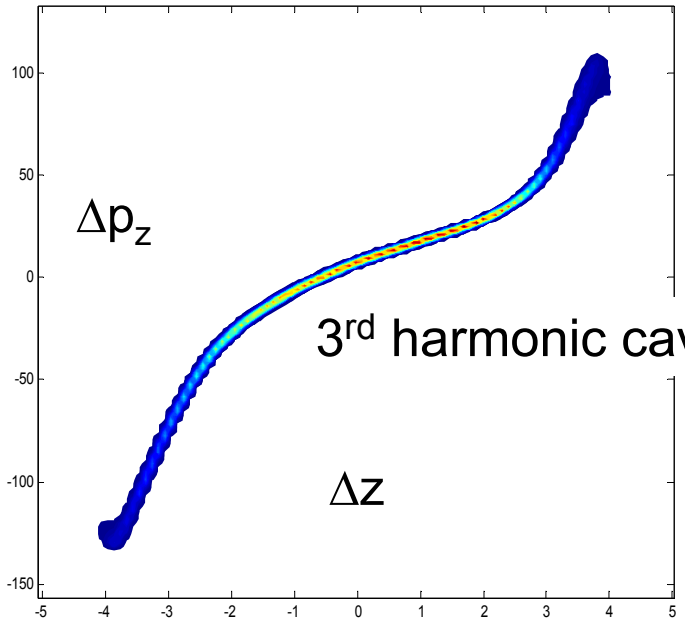
$\Rightarrow$ eventually fast orbit feedback in seed undulator

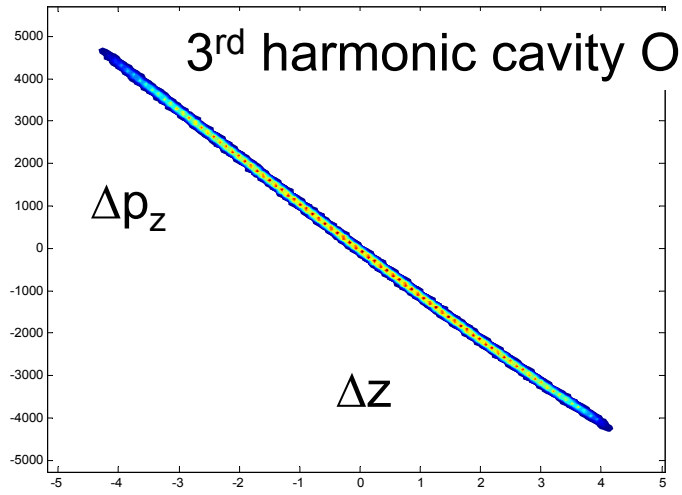
- **stable HHG parameter** (pulse energy, chirp, frequency …)
- good **temporal overlap** between electron bunch and laser pulse
- with 3th harmonic **cavity** $\sigma_t \sim 250$ fs @ few kA peak current

$\Rightarrow$ time jitter should be much smaller than $<< \sigma_t$ for reliable operation

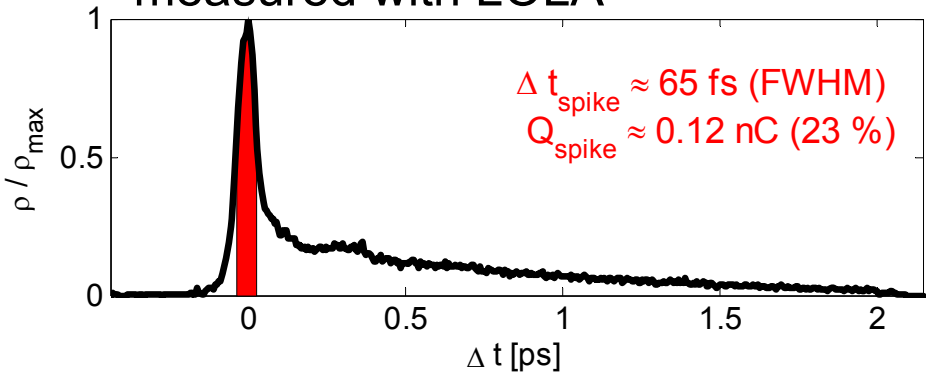
Requirements to electron beam

Longitudinal phase space without and with 3.9 GHz Module

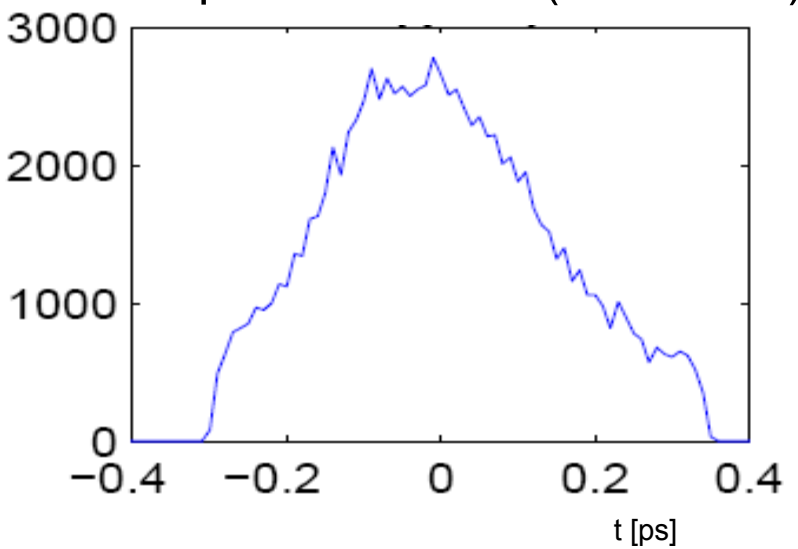




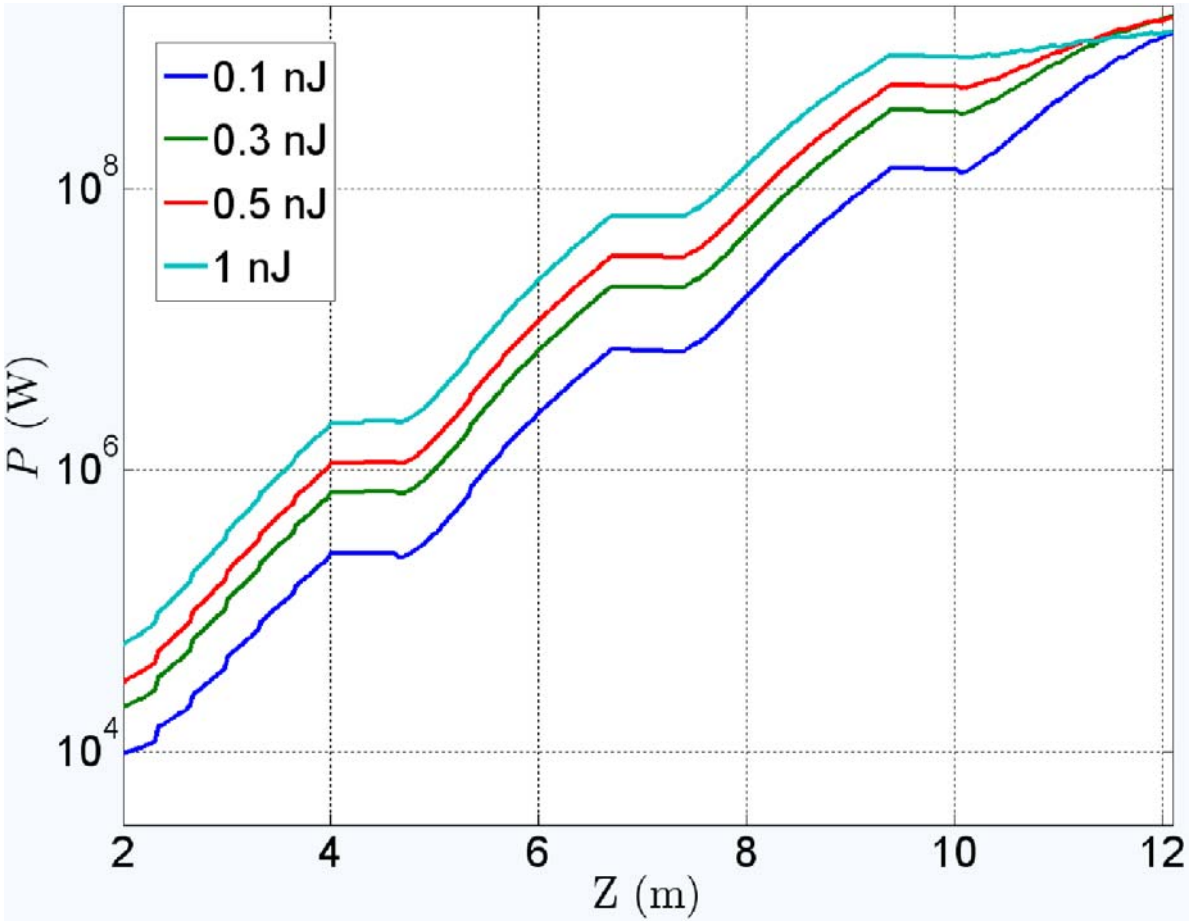
measured with LOLA

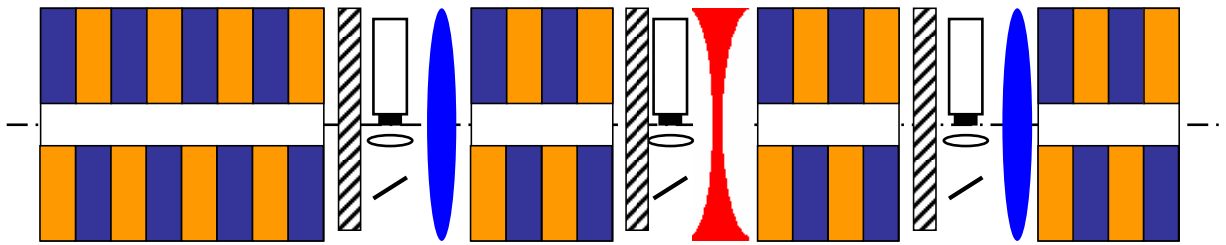


Compressed bunch (simulation)



Energy in the seeding pulse



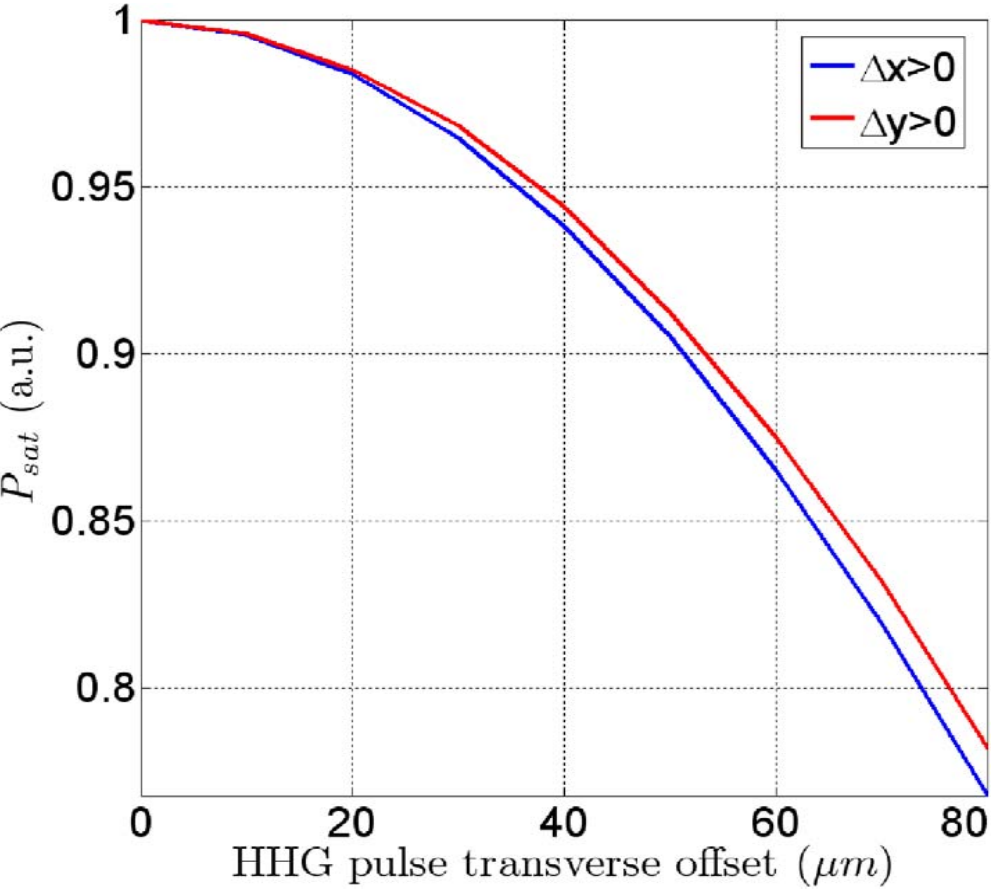


Radiation power in a seeded slice of the bunch at 30nm along the sFLASH undulators.

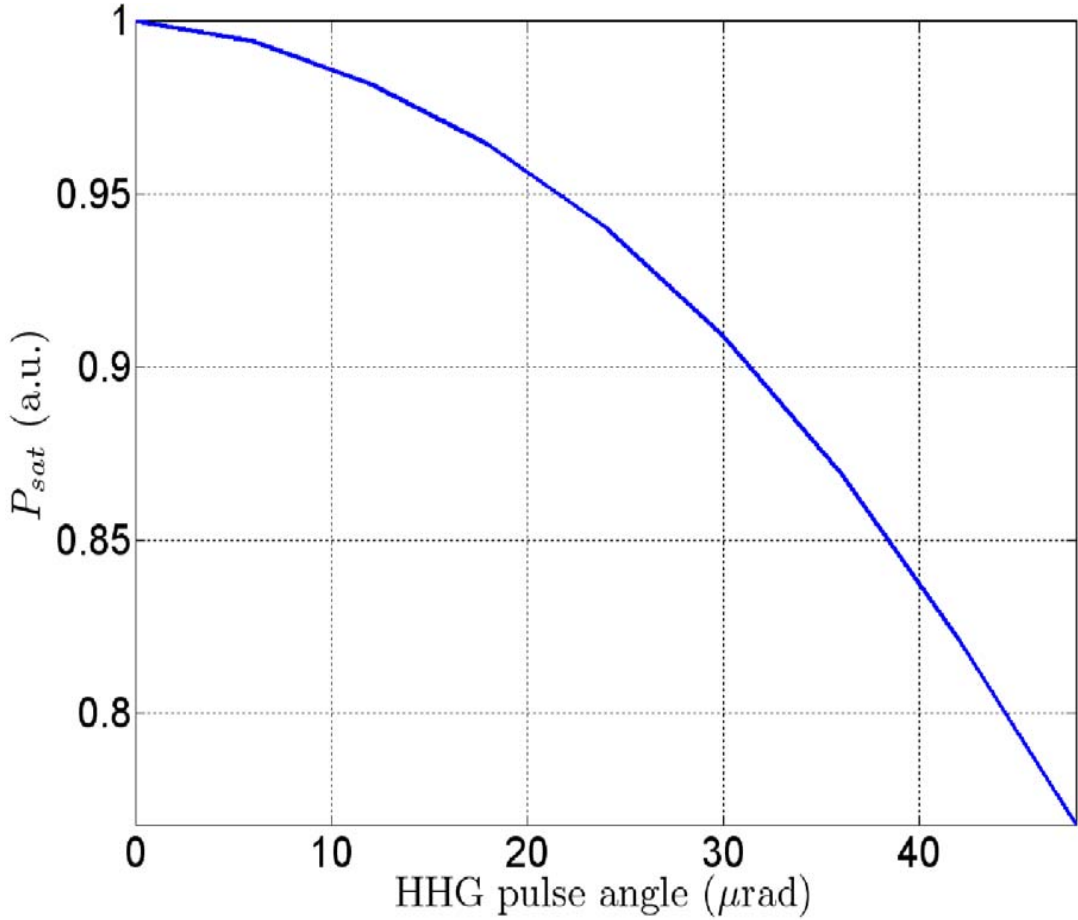
For **1 nJ** energy in the resonant harmonic the onset of the nonlinear regime is reached after three undulator sections, while for the 0.1 nJ case the exponential growth regime extents over the full undulator length without reaching saturation.

Transverse overlap tolerances

Radiation power vs. HHG seed transverse offset at the entrance of the sFLASH undulator.



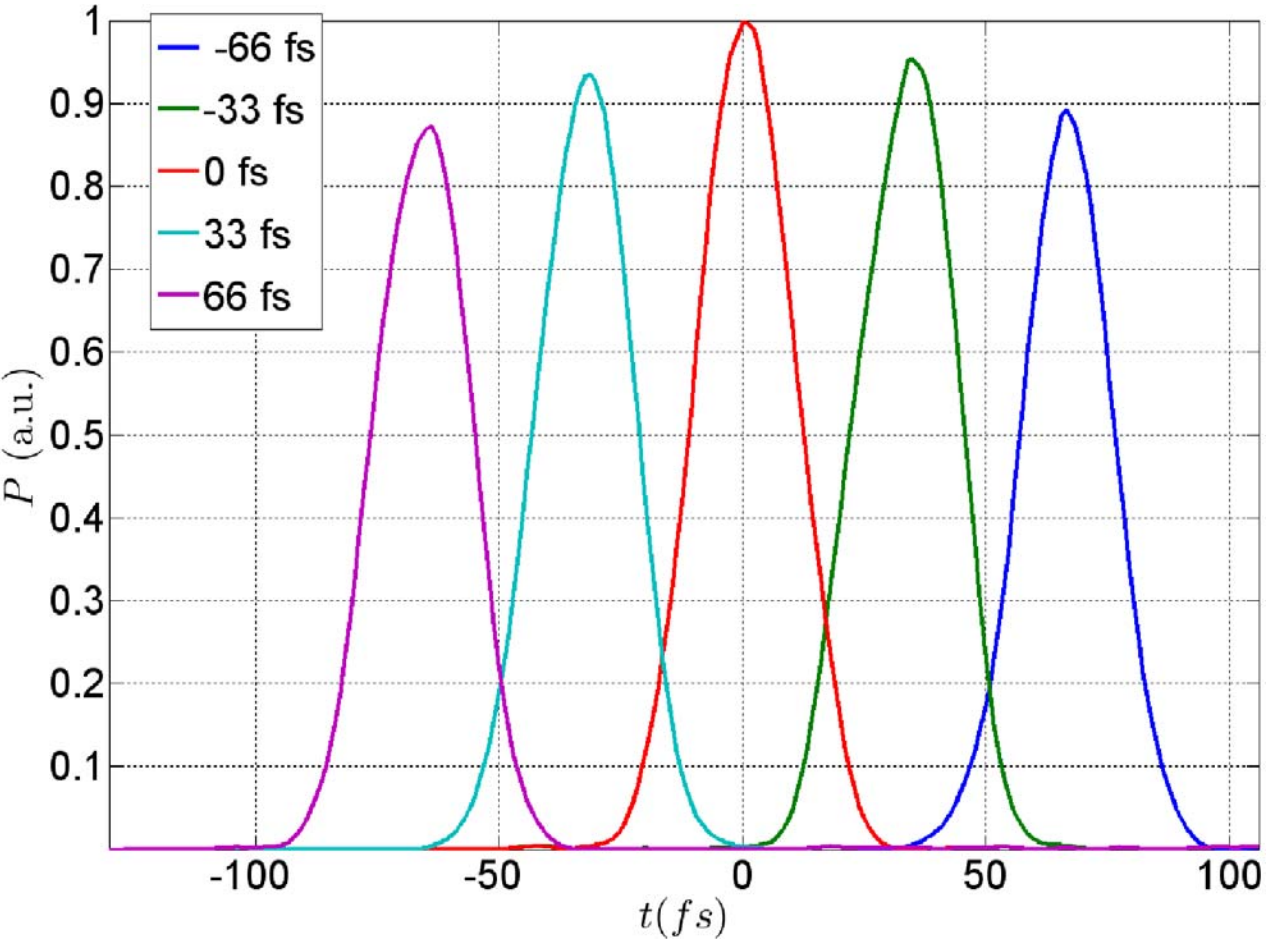
Radiation power vs. HHG seed angular offset at the entrance of the sFLASH undulator.



With a radiation power tolerance of **5%** one estimates the tolerances for the transverse offset **35 µm** and the angle **20 µrad** of the seed radiation.

Impact of the timing jitter

Longitudinal profiles of the FEL pulse at the onset of the nonlinear regime with different temporal offsets applied to the seed.



The electron bunch length of **630 fs FWHM** is about an order of magnitude larger than the maximal time offset. This mitigates the effect of the disturbed longitudinal overlap between the electron bunch and the HHG radiation to about **5%** FEL power reduction for the **~30 fs** offset.

Output radiation properties (GENESIS)

- consider the seeding beamline and electron optics as presented above
- λu=31.4 mm (PETRA III), 33 mm (PETRA II)
- duration HHG pulse: 20 fs (FWHM)
- energy of the 27th harmonic (29.6 nm): 1 nJ

transverse emittance, $\varepsilon_n = 2\ \mu$m

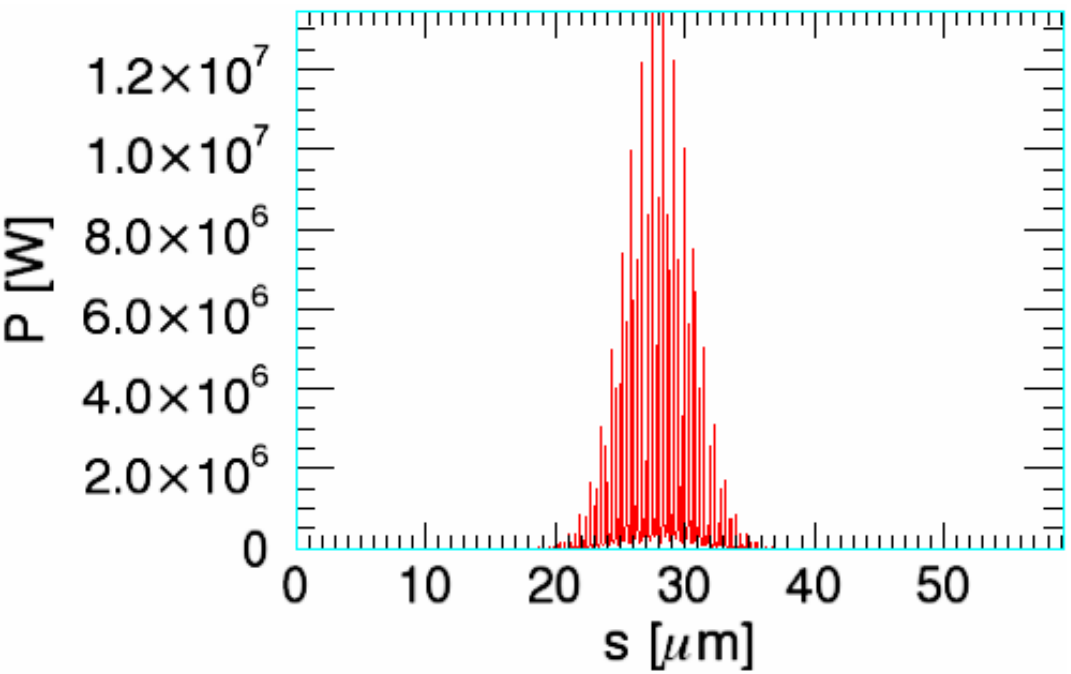
peak current, $I_{peak} = 1.5$ kA

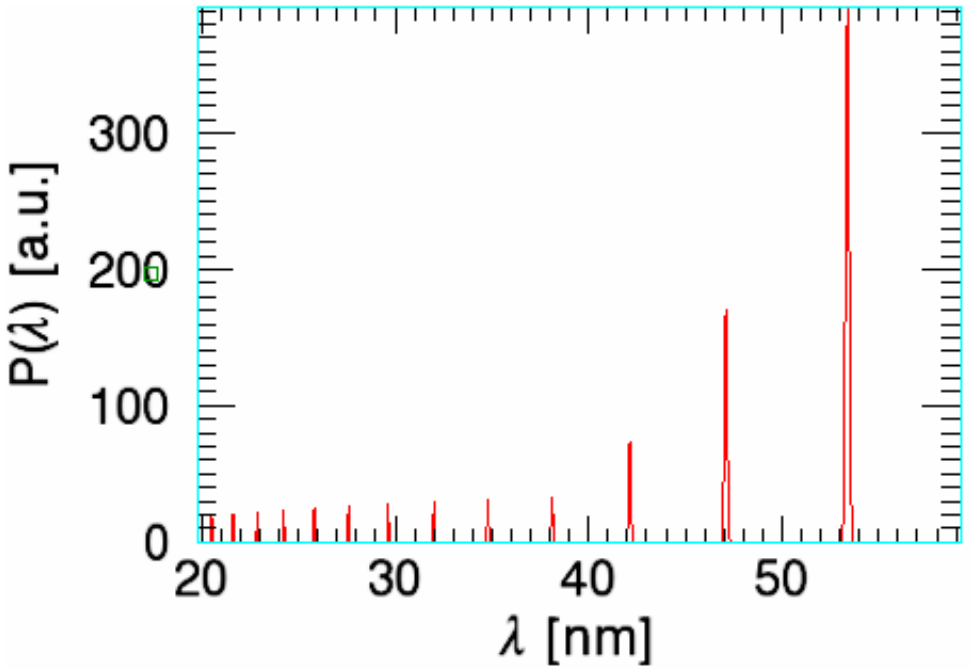
bunch length, $\sigma_z = 80\ \mu$m

E = 850 MeV

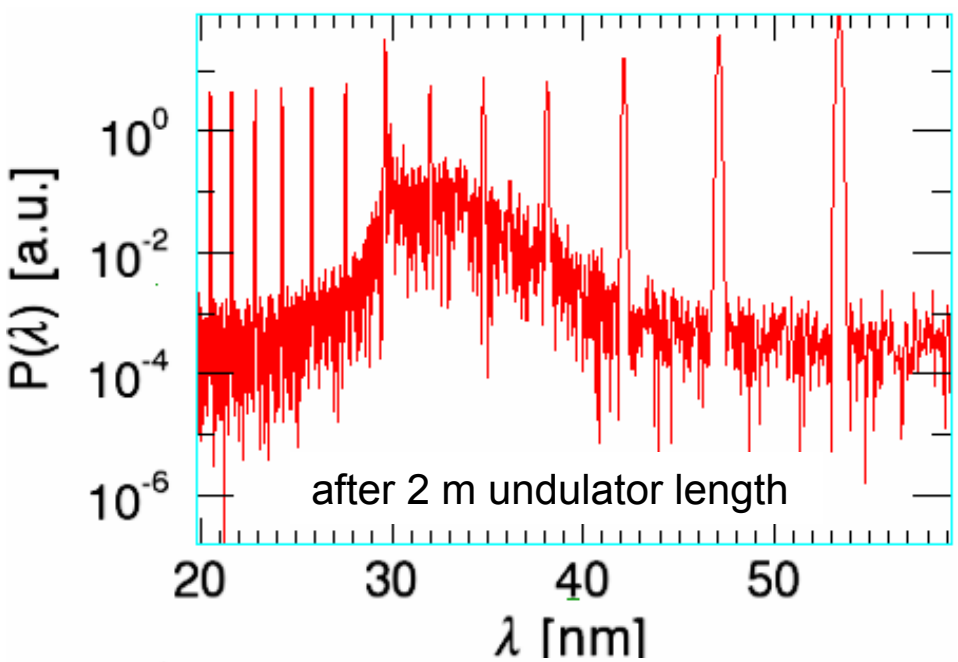
rms energy spread $0.2\ MeV$

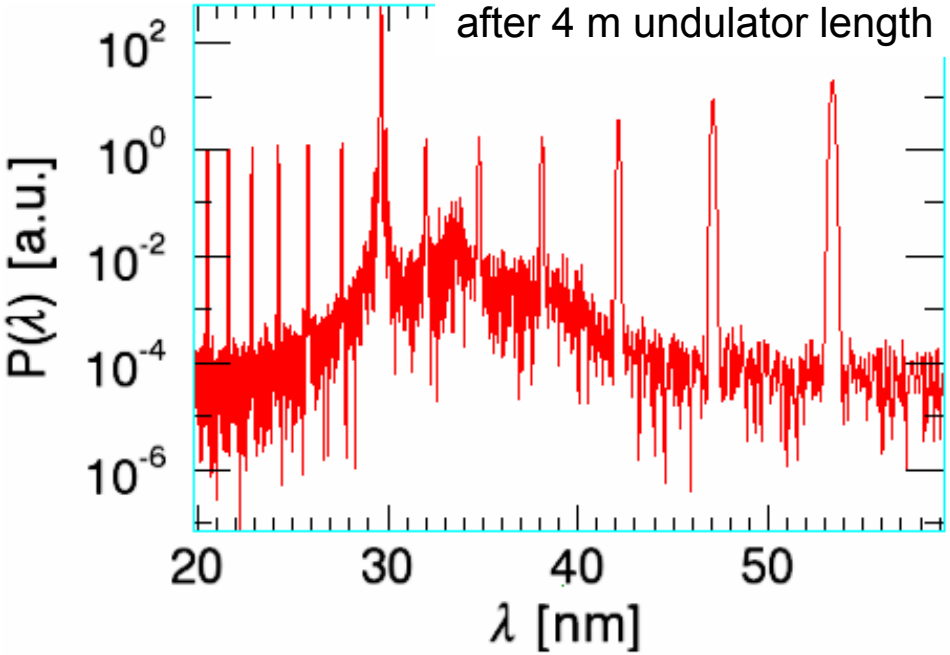
temporal profile and spectrum of the HHG seed

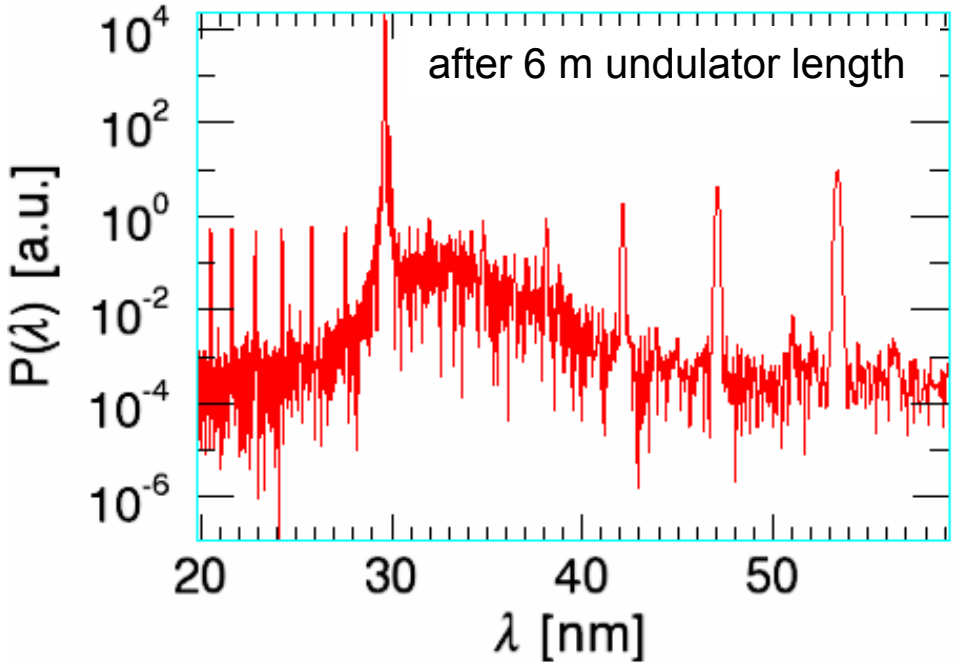


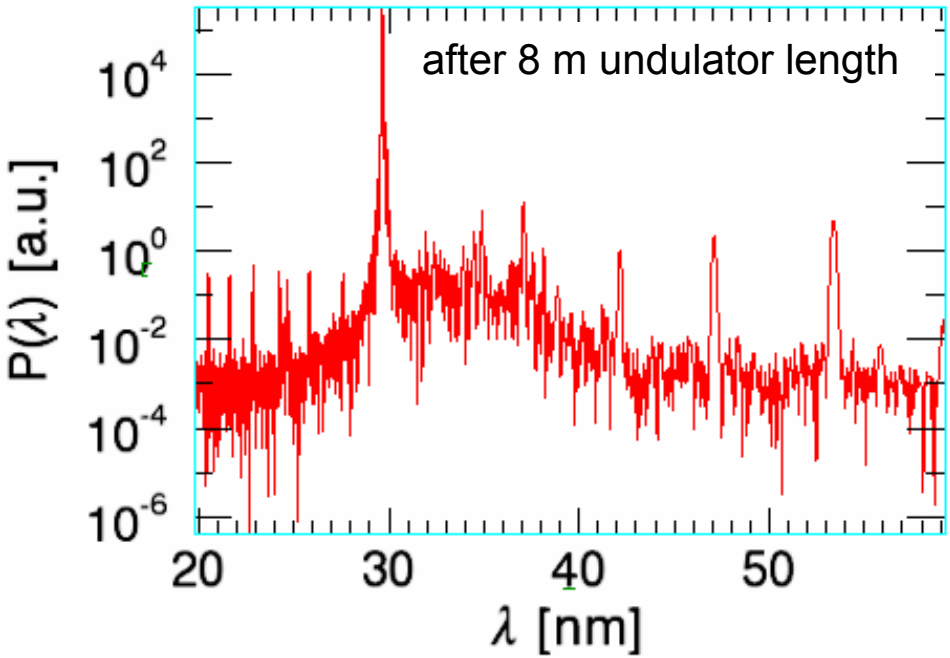


Spectrum along the sFLASH undulators

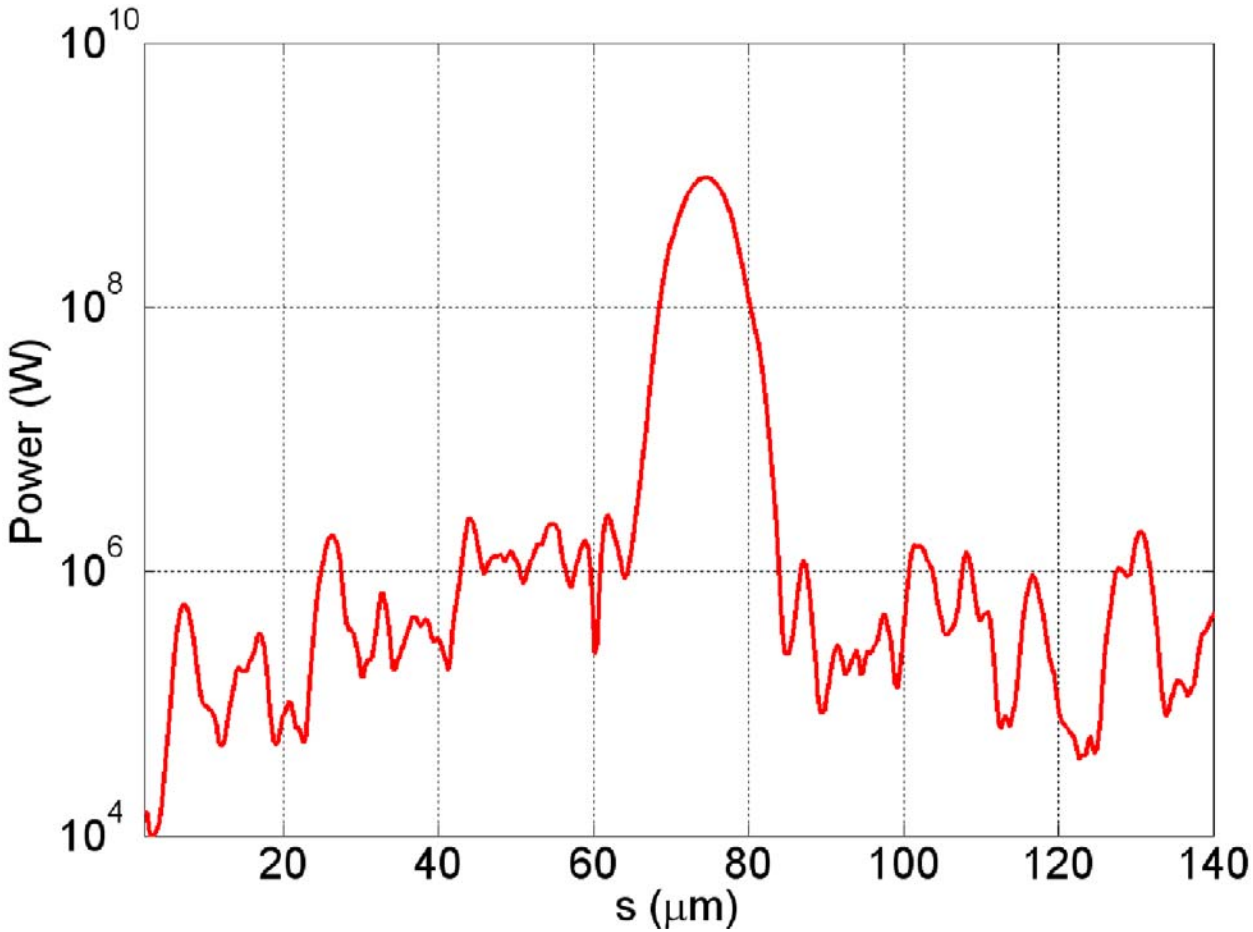








Output radiation properties



Radiation power at the onset of the nonlinear regime (about 8 m effective undulator length) as a function of the local distance in the bunch. The energy in the seeding harmonic is 1 nJ.

The amplified seed (around s=75 μm) exceeds the SASE power by about three orders of magnitude. The signal-to-noise ratio $E_{seeded}/E_{sase} \approx 80$, where $E_{seeded} \approx 24$ μJ is the energy in the seeded part of the bunch and $E_{sase} \approx 0.3$ μJ is the total energy in the SASE pulse

Present status and outlook

- Installation during the FLASH shutdown starting September 2009
- Undulators ordered, estimated delivery April 2009
- Undulator vacuum chambers in preparation
- Most of the other components (magnets, BPMs, WS, OTR) are available (re-used)
- Design and construction of diagnostic blocks ongoing
- Concept for undulator transport in tunnel ready. Construction ordered.
- Technical (3D) drawings of beamline in preparation.
- HHG drive laser delivered, installation work ongoing
- HHG source commissioning – spring 2009
- Design of coupling HHG seed->FLASH beamline ready, construction ongoing