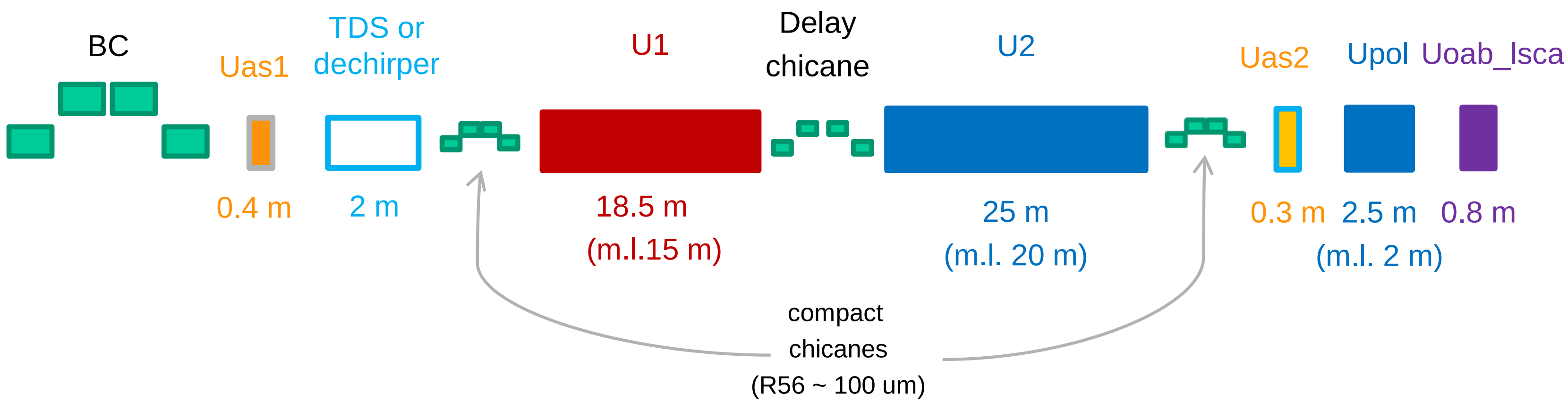
Attosecond options for FLASH2

E. Schneidmiller, B. Faatz, I. Hartl, T. Lang, B. Manschwetus,
M. Tischer, W. Wurth, M. Yurkov, J. Zemella …

Undulator line layout



U1: period 3.5 cm, Krms = 2.55

U2: period 2.7 cm, Krms = 1.45

Main FEL modes (for fixed energy 1.35 GeV):

- Harmonic lasing (5th in U1 and 3rd in U2): 1.2 – 2.3 nm
- Frequency doubling or reverse taper with harmonic afterburner: 1.2 – 2.3 nm
- HLSS: 2.2 – 6 nm
- SASE: 2.3 – 18 nm
- Two colors (SASE): 4.5 – 18 nm (U1) and 2.3 nm – 6 nm (U2+Upol)

Direct production of ~1 fs pulses

- New compression scheme should allow for production of ultra-short ~ (sub?)um bunches (or features) since the space charge effects are weaker by an order of magnitude, and final compression happens in front of the undulator (no bends, no dispersive areas in between)
- Either nonlinear compression or very low charge bunches (~10 pC) with linearized compression (close to or at full compression), would be continuation of Juliane's work towards even shorter bunches
- Laser heater may help to form the shape of the bunch
- Longitudinal space charge would still be strong, especially in the undulator, but the chirp can be compensated for by undulator taper
- At LCLS they get very short pulses (a couple of hundred attoseconds in hard X-ray regime) in a similar way
- At FL2 after upgrade one can reach ~1 fs at short wavelengths; short bunch can radiate NIR/vis pulse synchronized with soft X-ray pulse
- X-ray pulse is chirped: use monochromator or compressor to get sub-fs pulses
- Can be tried out at ~4 nm soon, 2-3 fs (FWHM) pulses might be available

Improvements due to new compression scheme

Simulations by J. Zemella (FLASH2020+ CDR)

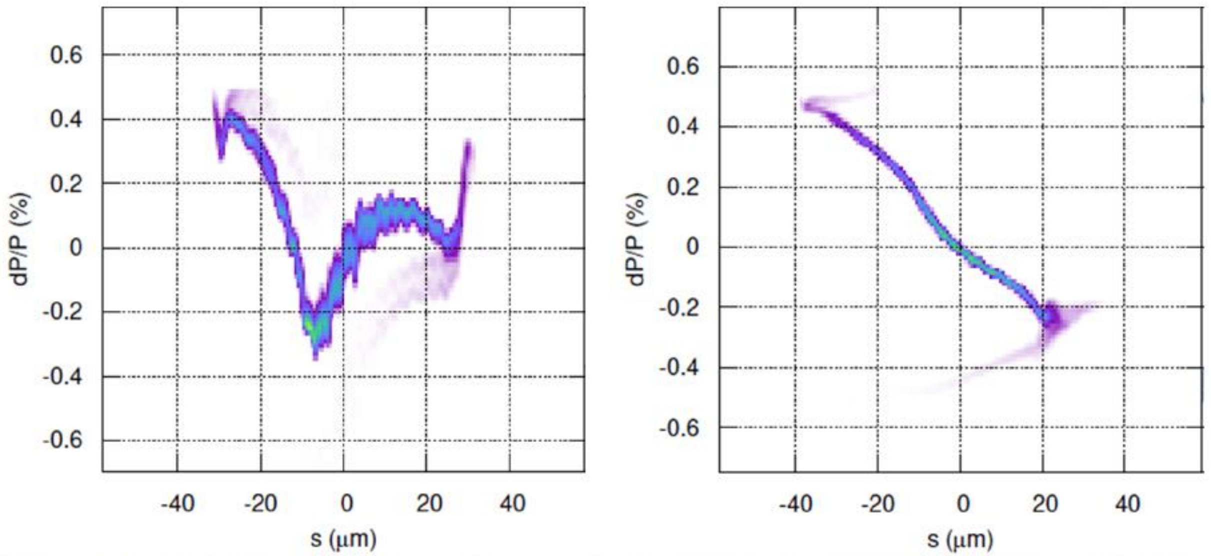
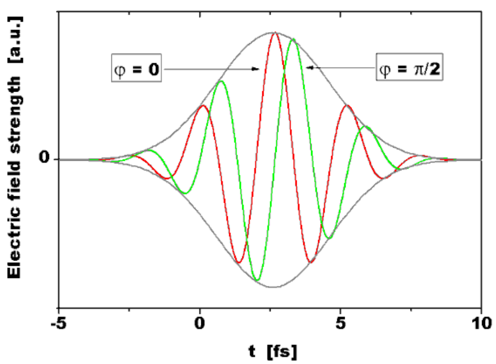
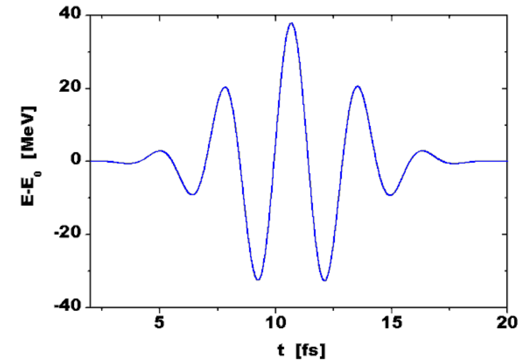


Figure 3.6 Longitudinal phase space in FLASH2 at 1.35 GeV with the present bunch compression scheme using two bunch compressors (left) and with the new scheme using a third compressor. The simulation includes space charge and CSR effects. The peak current in both cases is 2 kA, the bunch charge 250 pC.

Attosecond pulses: methods using few-cycle laser pulse



Two-period undulator



Laser pulse with carrier-envelope phase (CEP) stabilization (~ 1 mJ)

Energy modulation of electron beam

A. Zholents and W. Fawley, PRL 92(2004)224801

E. Saldin, E. Schneidmiller and M. Yurkov, Opt. Comm. 237(2004)153

E. Saldin, E. Schneidmiller and M. Yurkov, Opt. Comm. 239(2004)161

A. Zholents and G. Penn, PRST-AB 8(2005)050704

E. Saldin, E. Schneidmiller and M. Yurkov, PRST-AB 9(2006)050702

A. Zholents and M. Zolotorev, New J. Phys. 10(2008)025005

Y. Ding et al., PRST-AB 12(2009)060703

D. Xiang, Z. Huang and G. Stupakov, PRST-AB 12(2009)050702

Chirp-taper similarity: naïve picture

- Electrons with different energies in untapered undulator: red shift due to an energy offset
- Electrons with the same energy in a tapered undulator: red shift because K-value was larger at a retarded position
- The hope: combine chirp and taper with proper sign (positive chirp and negative taper or vice versa) and magnitude for a perfect compensation of gain degradation

Chirp-taper compensation effect

- Consider positive chirp and negative taper, no interaction
- Radiation slips forward towards higher energies, bunch propagates in the undulator towards higher K-values ➡ resonance is preserved
- Bunch is decompressed due to R56 of the undulator ➡ frequencies of density and energy modulations correspond to the radiation frequency at any position along the bunch and the undulator

$$\hat{\alpha} = -\frac{d\gamma}{dt}\frac{1}{\gamma_0\omega_0\rho^2}$$ energy chirp parameter

$$b_1 = -\frac{\lambda_w}{4\pi\rho^2}\frac{K(0)}{1+K(0)^2}\frac{dK}{dz}$$ taper parameter

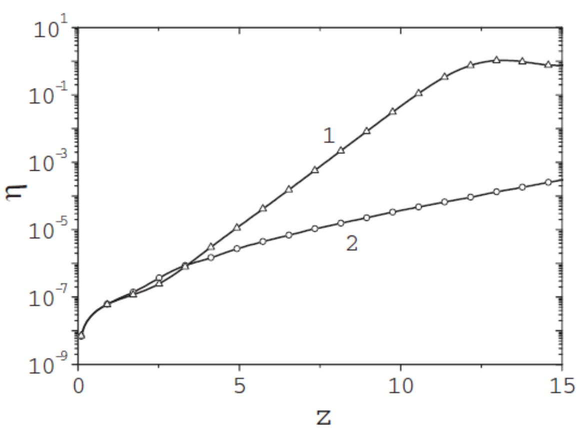
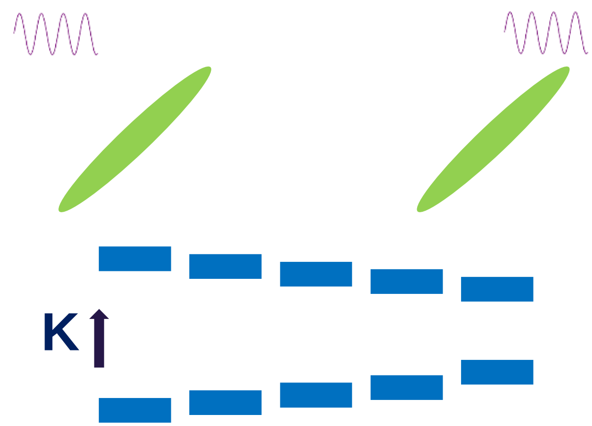


FIG. 3. Normalized power versus undulator length. Solid line 1: $\hat{\alpha} = 0$, $\hat{b}_1 = 0$; triangles: $\hat{\alpha} = 4$, $\hat{b}_1 = -2$; solid line 2: $\hat{\alpha} = 4$, $\hat{b}_1 = 0$; circles: $\hat{\alpha} = 0$, $\hat{b}_1 = 2$.



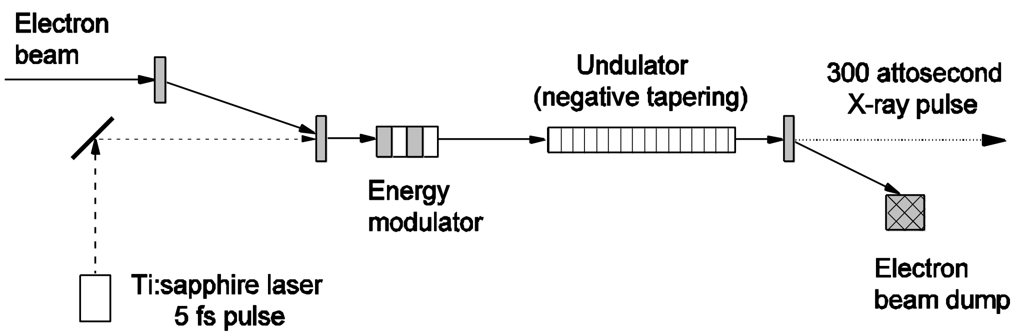
$$\frac{1}{H_{w0}}\frac{dH_w}{dz} = -\frac{1}{2}\frac{(1+K_0^2)^2}{K_0^2}\frac{1}{\gamma_0^3}\frac{d\gamma}{cdt}$$

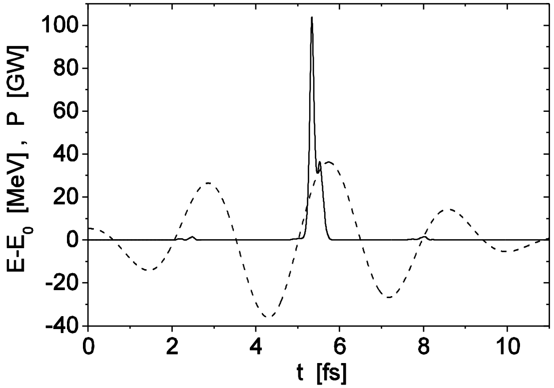
E. Saldin, E. Schneidmiller , M. Yurkov, Phys. Rev. ST-AB 9(2006)050702

Attosecond pulses: energy chirp and undulator taper

Energy chirp is perfectly compensated for by undulator taper

$$\frac{1}{H_{w0}}\frac{dH_w}{dz} = -\frac{1}{2}\frac{(1+K_0^2)^2}{K_0^2}\frac{1}{\gamma_0^3}\frac{d\gamma}{cdt}$$





E. Saldin, E. Schneidmiller and M. Yurkov, PRST-AB 9(2006)050702

High power, high contrast attosecond pulses

Studied by W. Fawley , NIMA 593(2008)111, for soft X-ray regime:
laser wavelength 2.2 um, modulation amplitude ~ 7 MeV for 2 GeV beam

How to get to 100 as scale at FLASH?

- Coherence time is not a fundamental limit, one can use different tricks to go to a shorter time scale
- Make use of the fact that the pulse is chirped

$$\hat{\alpha} = -\frac{d\gamma}{dt}\frac{1}{\gamma_0 \omega_0 \rho^2}$$

Method 1: use monochromator(Saldin, Schneidmiller, Yurkov, Phys. Rev. ST-AB 9(2006)050702), the pulse length reduction factor can be up to $\sqrt{2\hat{\alpha}}$

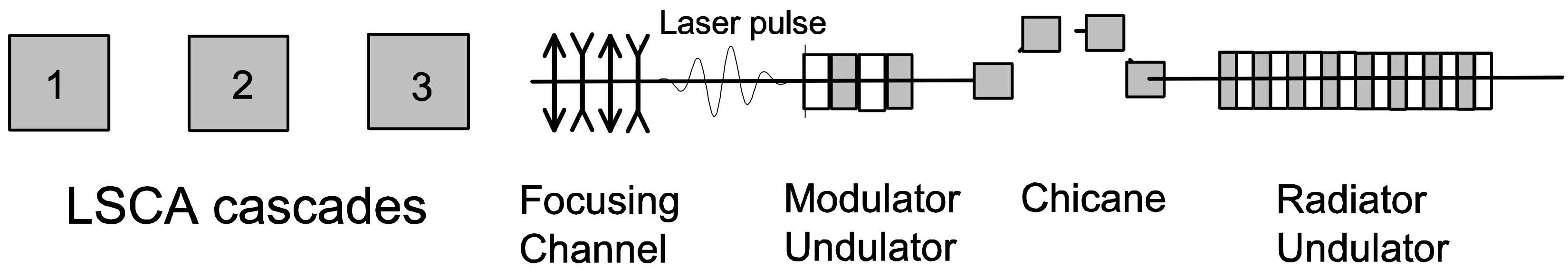
Method 2: use pulse compressor, the pulse length reduction factor can be up to $2\hat{\alpha}$

Parameter $\hat{\alpha}$ can be about 3 to 5 for our parameter range so that a significant reduction of pulse duration might be possible. In both cases the laser WL should be in the range 2-3 um.

How to get to 100 as scale at FLASH?
(a new scheme)

- Use a shorter WL laser (like Ti:Sapphire, 800 nm) and chirp-taper scheme
- Lasing slice is shorter than FEL coh. length: larger saturation length (but we have a big reserve at 5-6 nm) but the pulse length is still on the order of coherence length due to slippage
- Use the last chicane for a moderate compression of the lasing slice in the electron beam: detune the frequency from that coming from the main undulator, compress WL and the length of lasing slice, increase bunching;
- Block background radiation from the main undulator
- Let this slice radiate in a short radiator (~ 10 periods) tuned to the compressed WL; the rest of the bunch is not resonant here
- Estimates show that it should work down to 100 as but the simulations are required

LSCA-based attosecond scheme



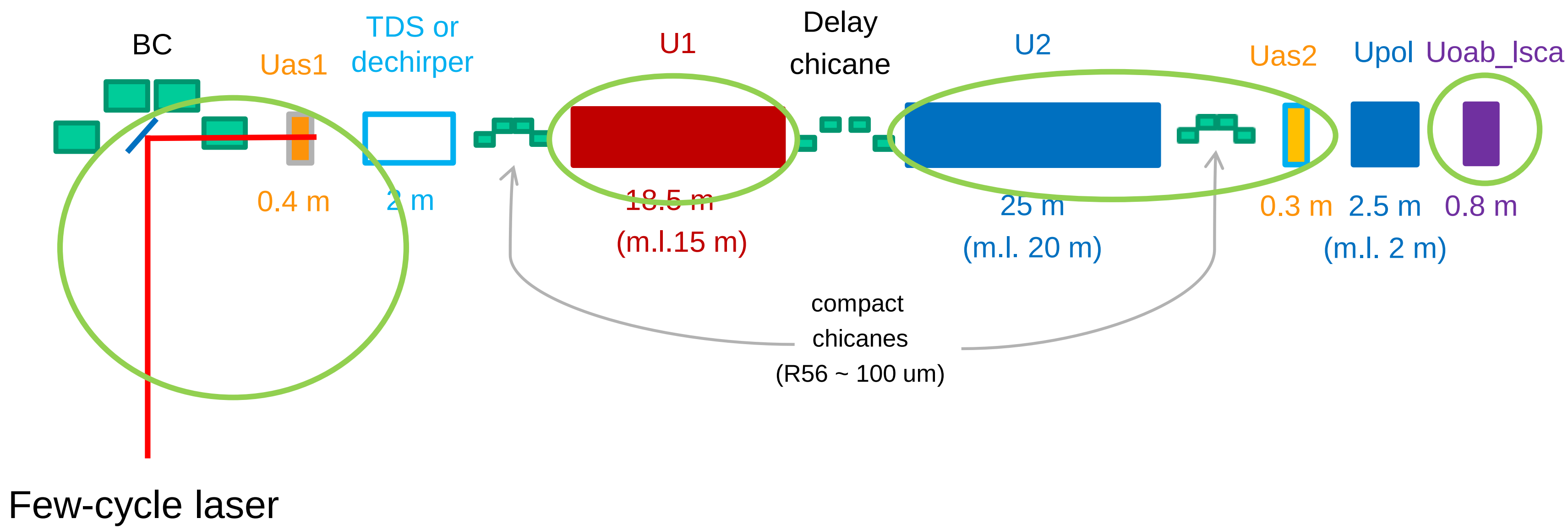
First cascades are used to amplify shot noise. In the last cascade after a drift the beam is modulated by a few-cycle laser pulse. In the last compressor (with reduced R56) a short slice is compressed: WL compression and final amplification to saturation. The radiator undulator is tuned to the compressed WL.

Too futuristic scheme

E. Schneidmiller and M. Yurkov, PRST-AB 13(2010)110701

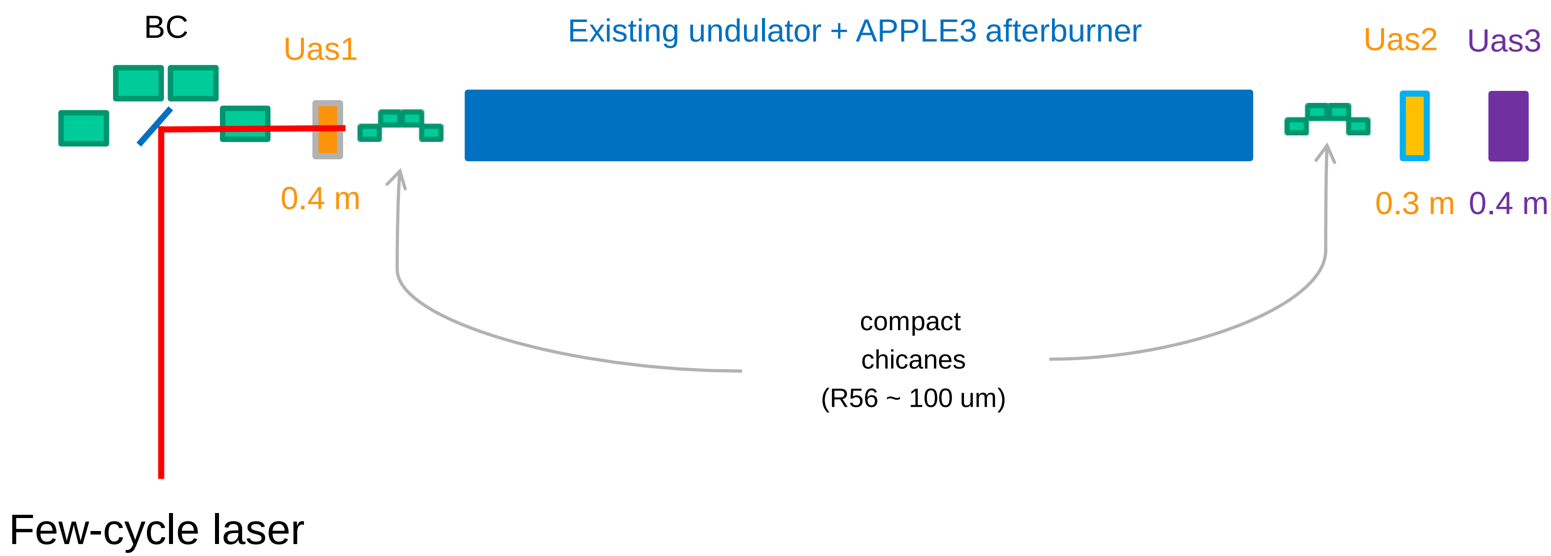
M. Dohlus, E. Schneidmiller and M. Yurkov, PRST-AB 14(2011)090702

FL2 upgrade: attosecond pulses



- Undulator Uas1: two periods, period length ~ 15 cm
- Undulator Uas2: ten periods, period length ~ 3 cm
- Two attosecond pulses of different colors are, in principle, possible: split and delay laser pulse, make two separated modulation areas, use TDS or dechirper to make them lase in U1 and U2, use delay chicane to control delay
- Or produce few-cycle optical radiation in Uoab_lsca undulator, transport it together with soft X-ray beam, do cross-correlation with PP laser at the experiment

Minimalistic upgrade for attosecond pulses



- Undulatosr Uas1 and Uas3: two periods, period length ~ 15-20 cm
- Undulator Uas2: ten periods, period length ~ 3 cm

For this upgrade we need to move SASE13 and SASE14 upstream

Estimates of laser parameters

We need two-cycle pulses. WL and pulse energy depend on a scheme. Crude estimates of pulse energies:

- Laser with 2-3 um wavelength: a few mJ
- Ti:Sapphire (800 nm) for FEL-based scheme with compression of a slice: sub-mJ range

CEP stability: ~ 100 mrad

Timing and synchronization

- Timing requirement: overlap of the laser pulse with lasing part of electron bunch. For 250 pC bunch a reasonable estimate would then be ~ 10 fs.
- Synchronization with sub-femtosecond precision between the machine and experiments is a big challenge. We could rather produce the second color (VIS/NIR) with the same bunch in a long period undulator at the end; then transport both colors to experiments using the same optical elements; finally do cross-correlation measurement with a powerful laser on a table and sort out the data accordingly. Thus, sub-cycle synchronization might be possible.