PAUL SCHERRER INSTITUT

PSI

Progress on Fresh-slice Multi-stage Amplification at SwissFEL

Guanglei Wang

31.08.2023

Luzern, FLS 2023

Introduction

- Standard FEL pulses have durations of tens of femtoseconds

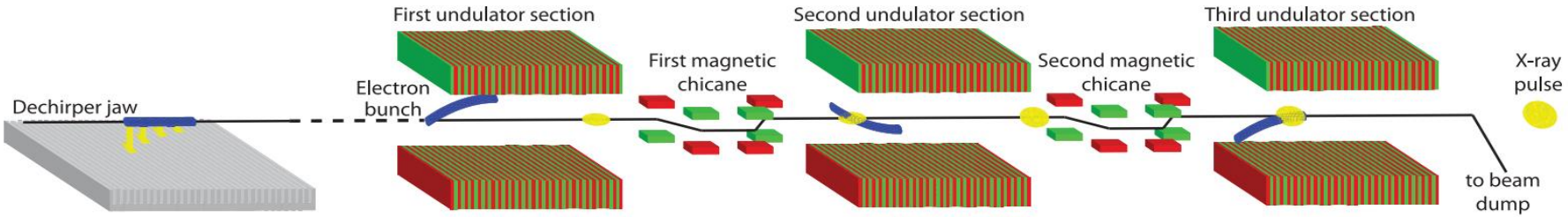
- Short FEL pulses can be achieved by:
  - Strongly compressing a low charge electron beam
  - Spoiling most of the electron beam for standard charges (e.g. with beam tilt, slotted foil, ESASE, etc.)

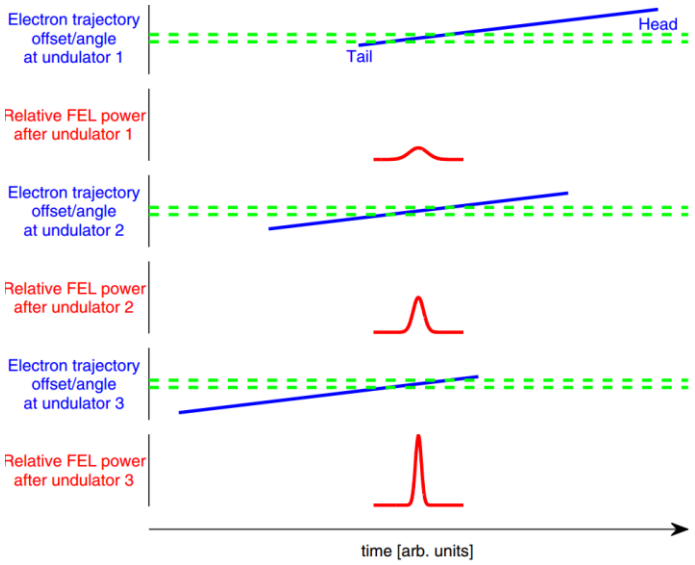
- There is a strong interest to increase the power of short FEL pulses

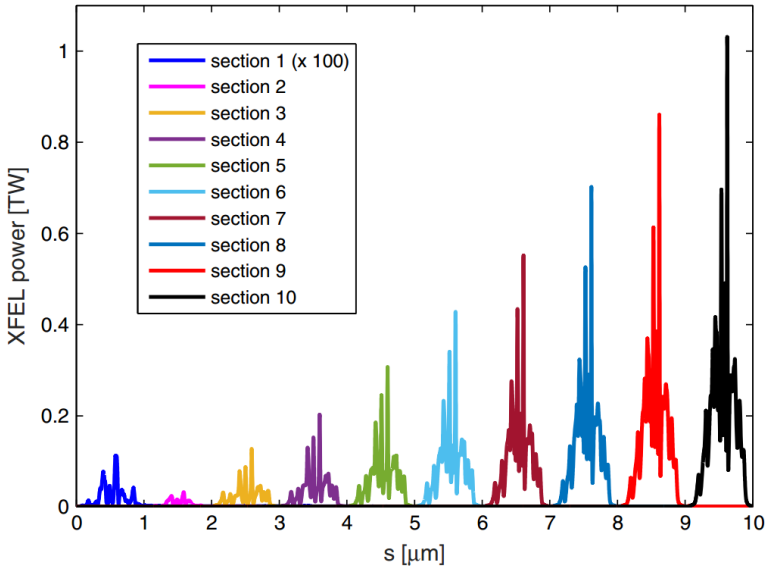
- Method: fresh-slice multi-stage amplification schemes based on superradiance
  - A short pulse is produced in a first undulator stage
  - This pulse is later amplified in several stages by fresh electrons
  - Need chicanes to delay the electron beam
  - Need to tailor the beam so that fresh electrons are provided (e.g. beam tilt, ESASE with uneven separation of current spikes)

Fresh-slice multi-stage amplification with tilted beam

- Lasing part of e-beam is femtosecond to attosecond, TW level FEL output (simulation)
- Experimental demonstration in LCLS: few hundreds of uJ for few fs



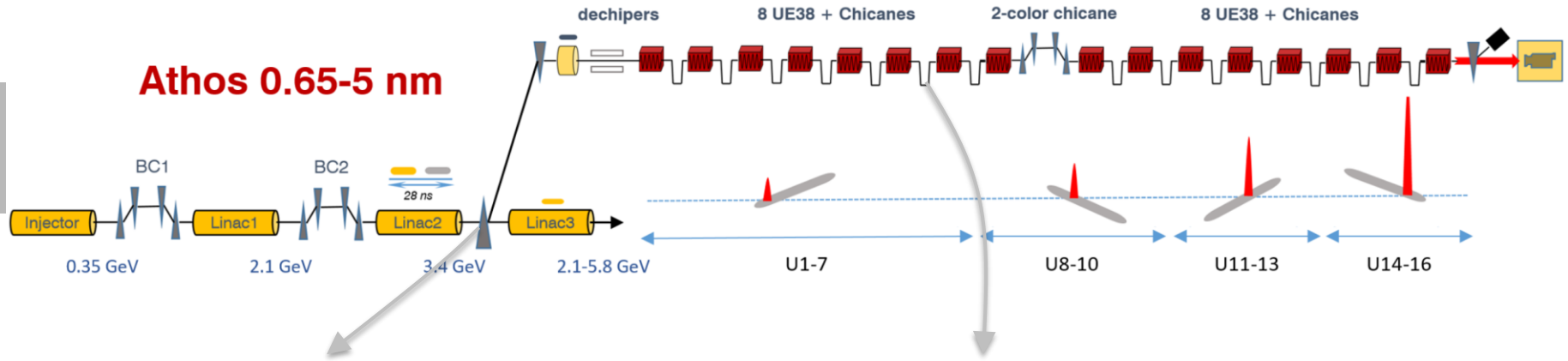




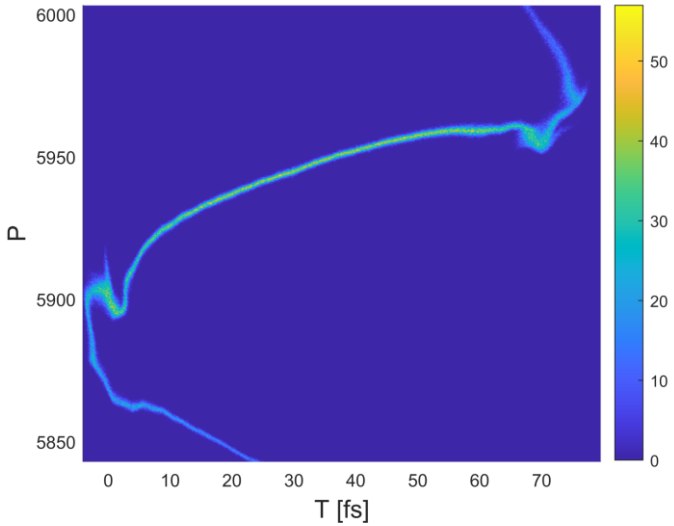
Eduard Prat et al., Phys. Rev. ST Accel. Beams 18 (2015) 100701

Alberto A. Lutman et al., Phys. Rev. Lett. 120 (2018) 264801

Fresh-slice multi-stage amplification in Athos



Simulation result of e-beam longitudinal phase space (LPS)



Tilt can be produced in 2 ways:

1. Dispersion in the switchyard (used method due to linear streaking and less losses)
2. Dechirper wakefields

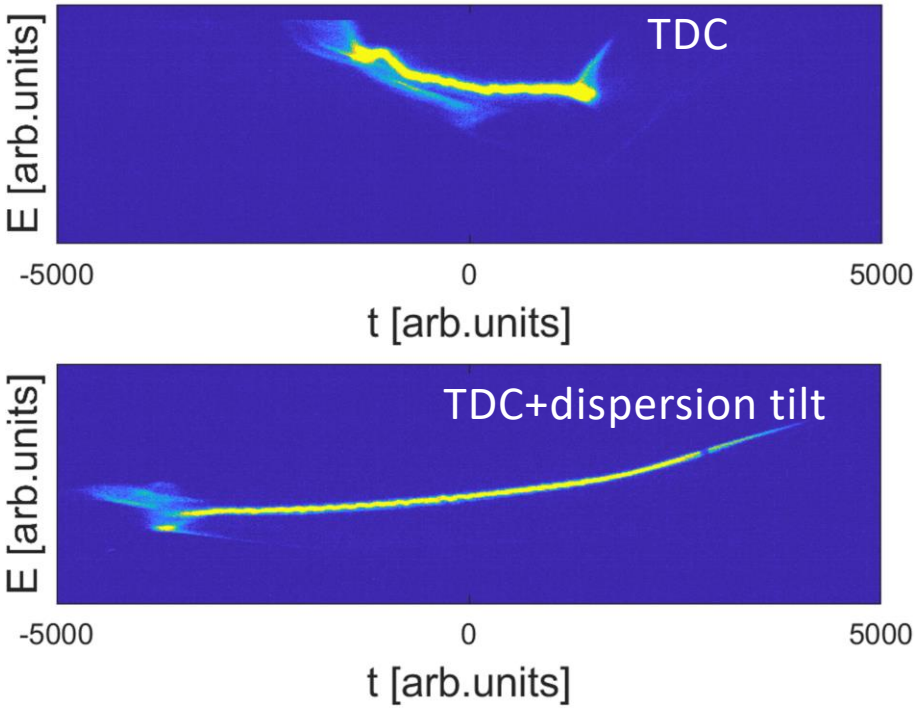
16 Apple X undulator +

Chicanes for High power and Improved Coherence

- CHIC is a core component in MSA scheme, used to achieve time and transverse overlap between the stages (delay~5 fs, offset~ $\pm$ 400 µm)
- We use the optical klystron to reduce the saturation length in the first stage
- Orbit feedback in undulator is essential: we currently have independent feedbacks for up to 4 regions

LPS measurements with TDC and dispersion

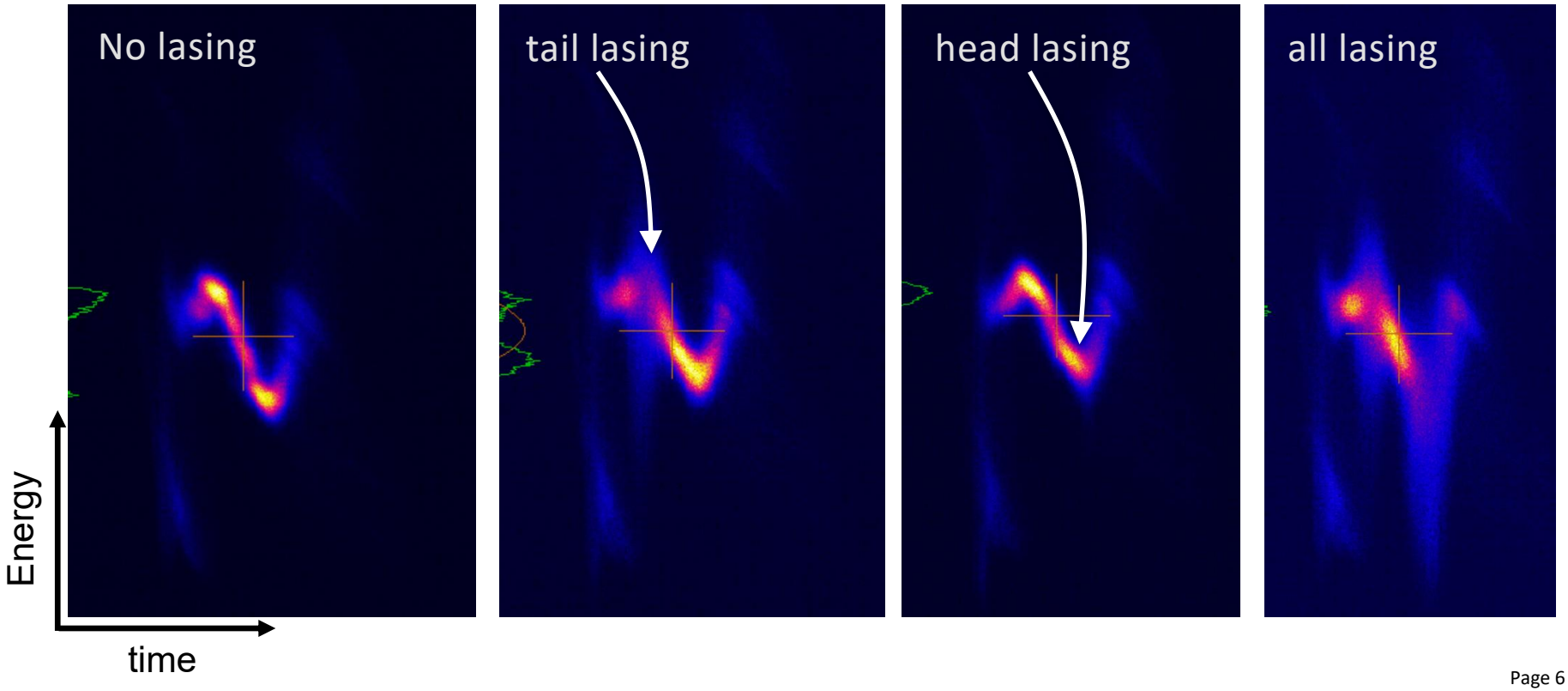
- Measurements after the undulator at the Athos dump (dispersive in Y, streaking in X)
- Streaking with X-band transverse-deflector cavity (TDC) and dispersion
- With dispersion, streaking increases by a more than a factor of 2 → resolution < 500 as



- Comparing lasing on and off conditions → FEL power profile reconstruction
- Post undulator LPS measurements are fundamental to setup and optimize the scheme

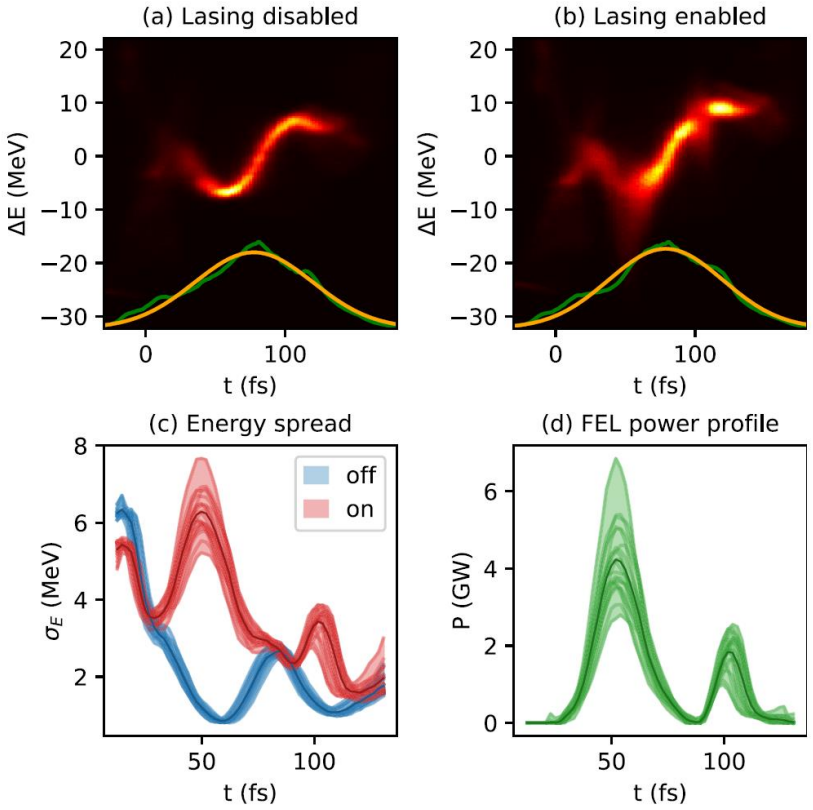
First experimental demonstration at Athos with 2-stages

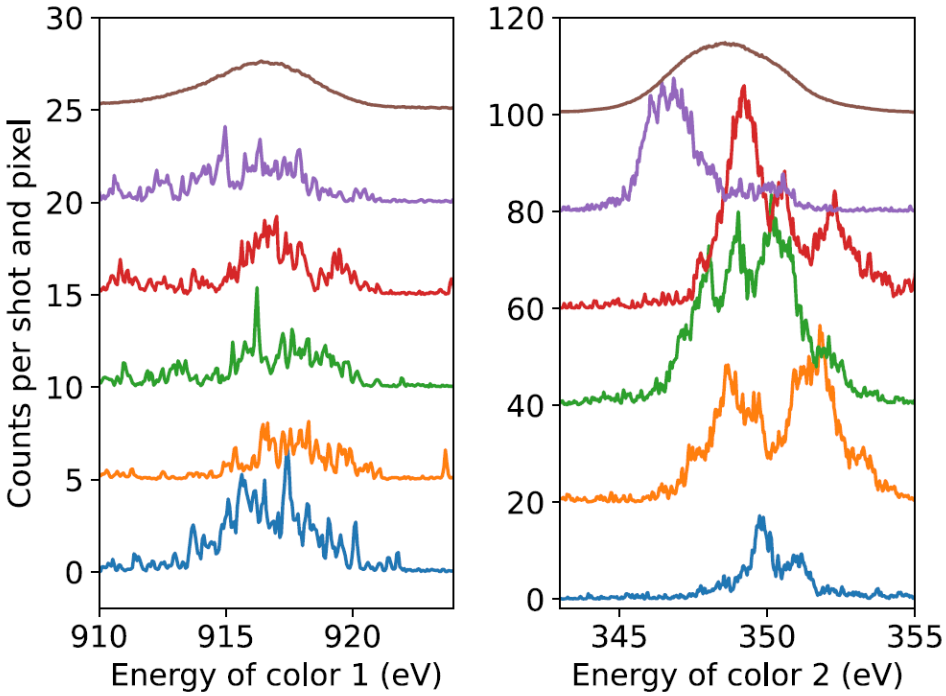
- 8+8 undulator modules. Two-color chicane used to overlap two fractions in time. Orbit feedback used for transverse overlap
- FEL pulse energy from 2nd undulator section is amplified by more than 5 times, from 20 µJ to about 140 µJ
- FEL pulse duration is about 4 time shorter than normal operation in Athos
- Streaking by dispersion only is used to diagnose FEL beam (X-band TDC not available at that time)



Two-color generation with fresh slice

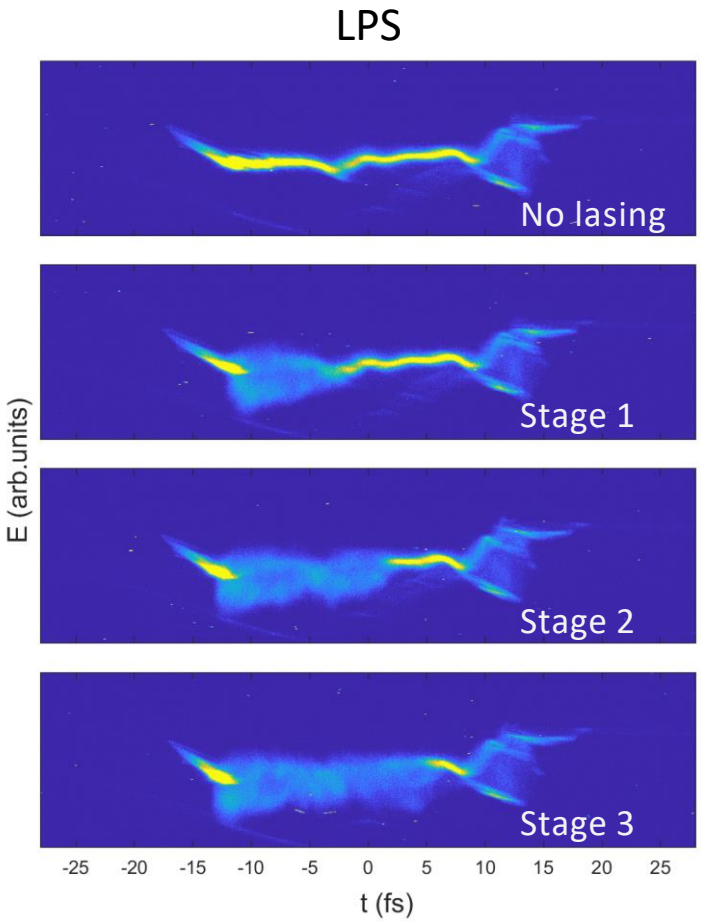
- "2 stage amplification without overlap" → 2 colors in fresh slice mode
- 2 color chicane used to scan the delay between the 2 pulses (from ~-30 fs to ~500 fs)
- K used to tune the photon energies (demonstrated 350 and 915 eV)
- Pulse energies between ~10 and ~300 µJ for each color, pulse duration down to few fs rms.
- Mode extensively used in Athos

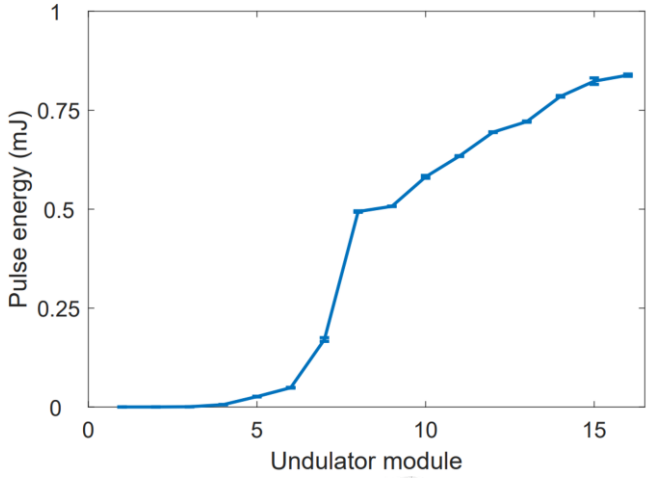




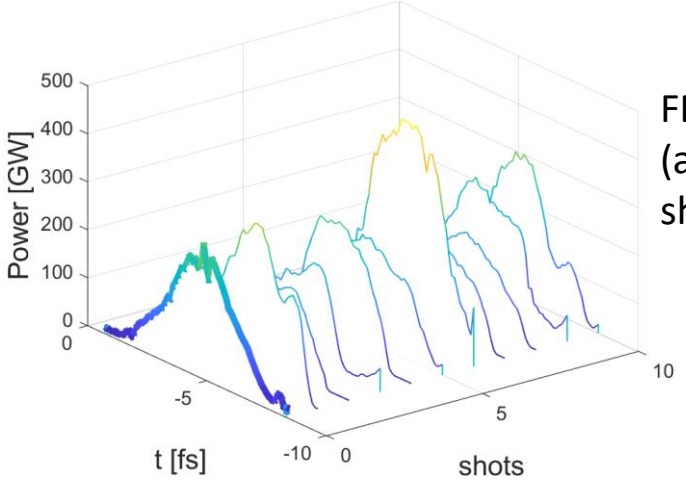
Prat, E., et al., Widely tunable two-color x-ray free-electron laser pulses. *Physical Review Research*, *4*(2), L022025 (6 pp.).

3-stage fresh slice amplification @ 1 keV





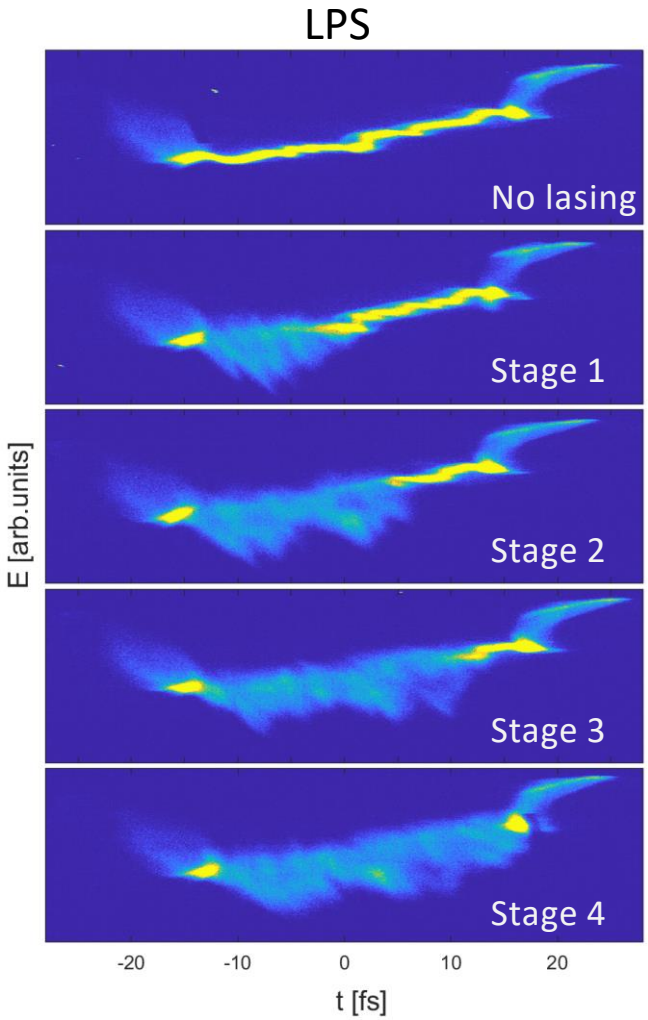
Gain curve

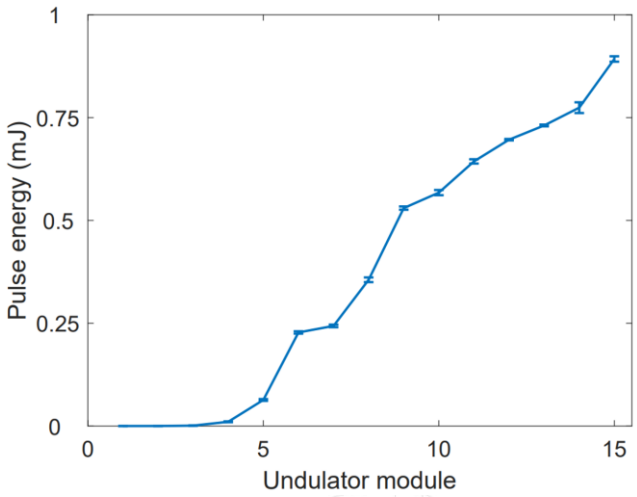


FEL power profiles (average in bold & shot to shot)

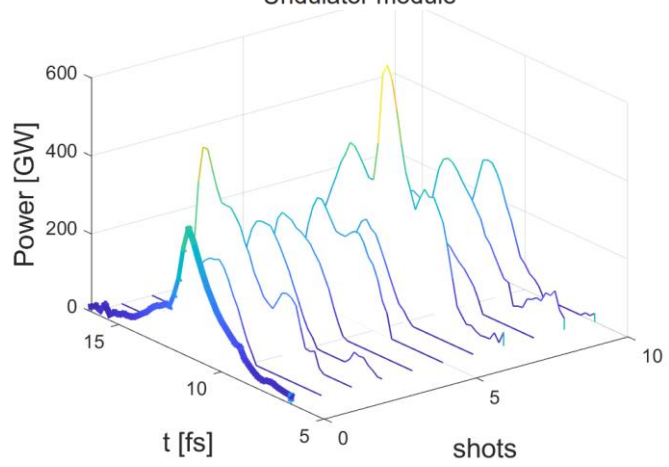
- 1st stage up to FEL saturation, next stages amplify the short FEL pulse, practically all bunch contributes to the FEL process
- Final FEL pulse with an average pulse energy of 0.86 mJ, and preliminary analysis shows that the reconstructed average peak power is 278±88 GW, with a pulse duration of 1.36±0.17 fs (RMS)

4-stages fresh-slice amplification @520 eV





Gain curve



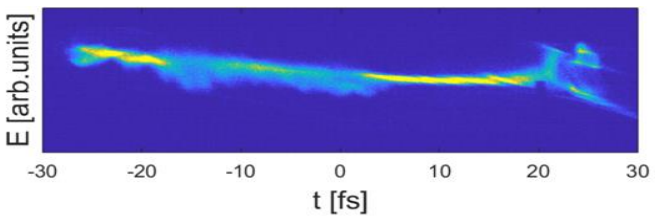
FEL power profiles (average in bold & shot to shot)

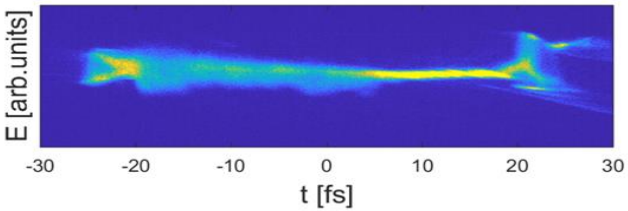
- 1st stage up to FEL saturation, next stages amplify the short FEL pulse, practically all bunch contributes to the FEL process
- Final FEL pulse with an average pulse energy of 0.91 mJ, and preliminary analysis shows that the reconstructed average peak power is 341 ± 145 GW, with a pulse duration of 1.32±0.56 fs (RMS)

FEL pulse duration control @ 1 keV (3 stages)

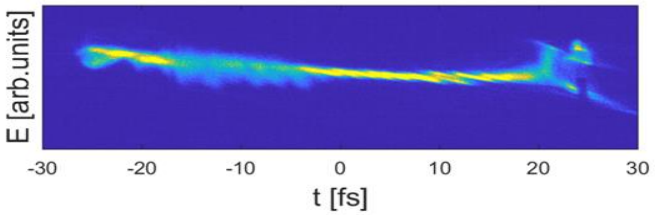
Short/1.4 fs

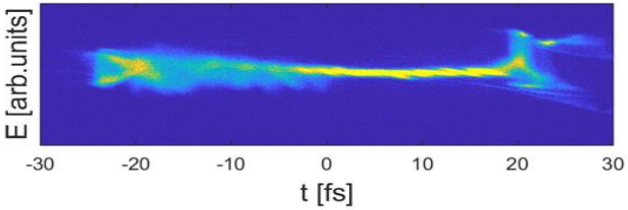
Long/2.1 fs



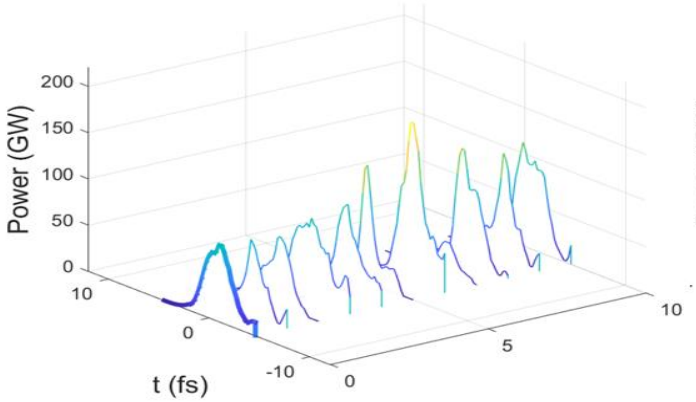


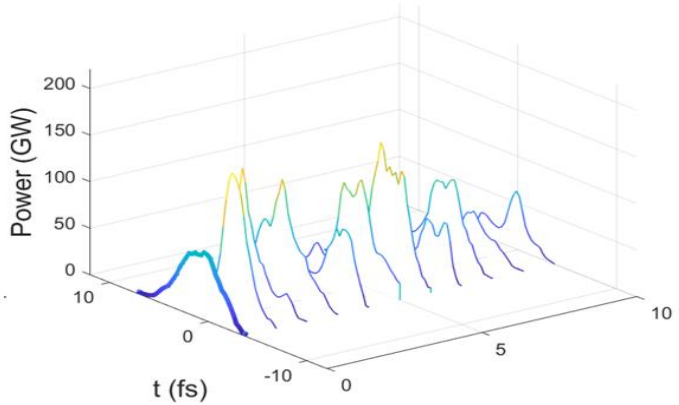
3 stages





2 stages



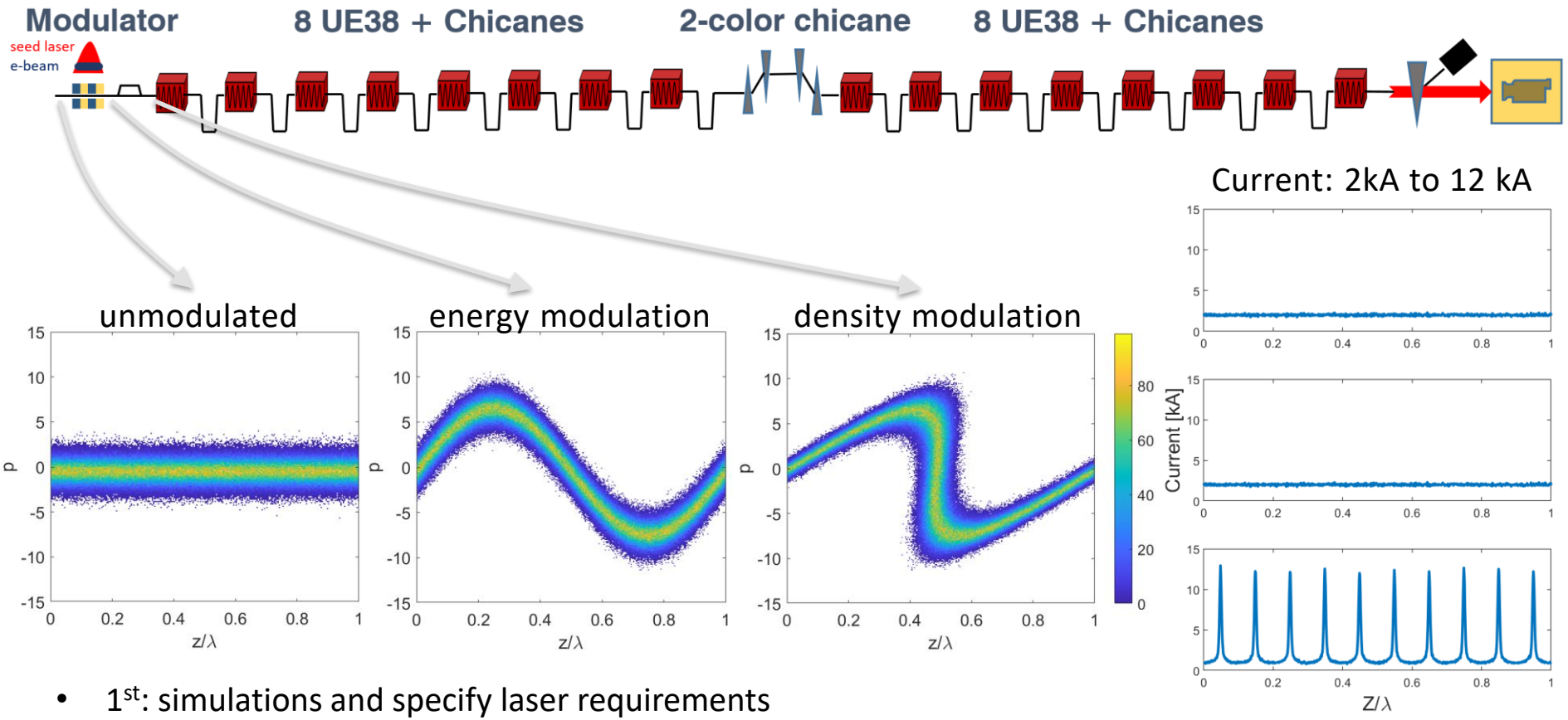


FEL power profiles (average in bold & shot to shot)

- The FEL pulse duration can be controlled by adjusting the tilt amplitude (more tilt less energy but shorter pulse). Results: 1.4 to 2.1 fs (RMS), with a pulse energy of 290, 440 uJ
- The peak power for the two different FEL pulse duration is similar at around 100 GW

Outlook: fresh-slice multi-stage amplification with ESASE

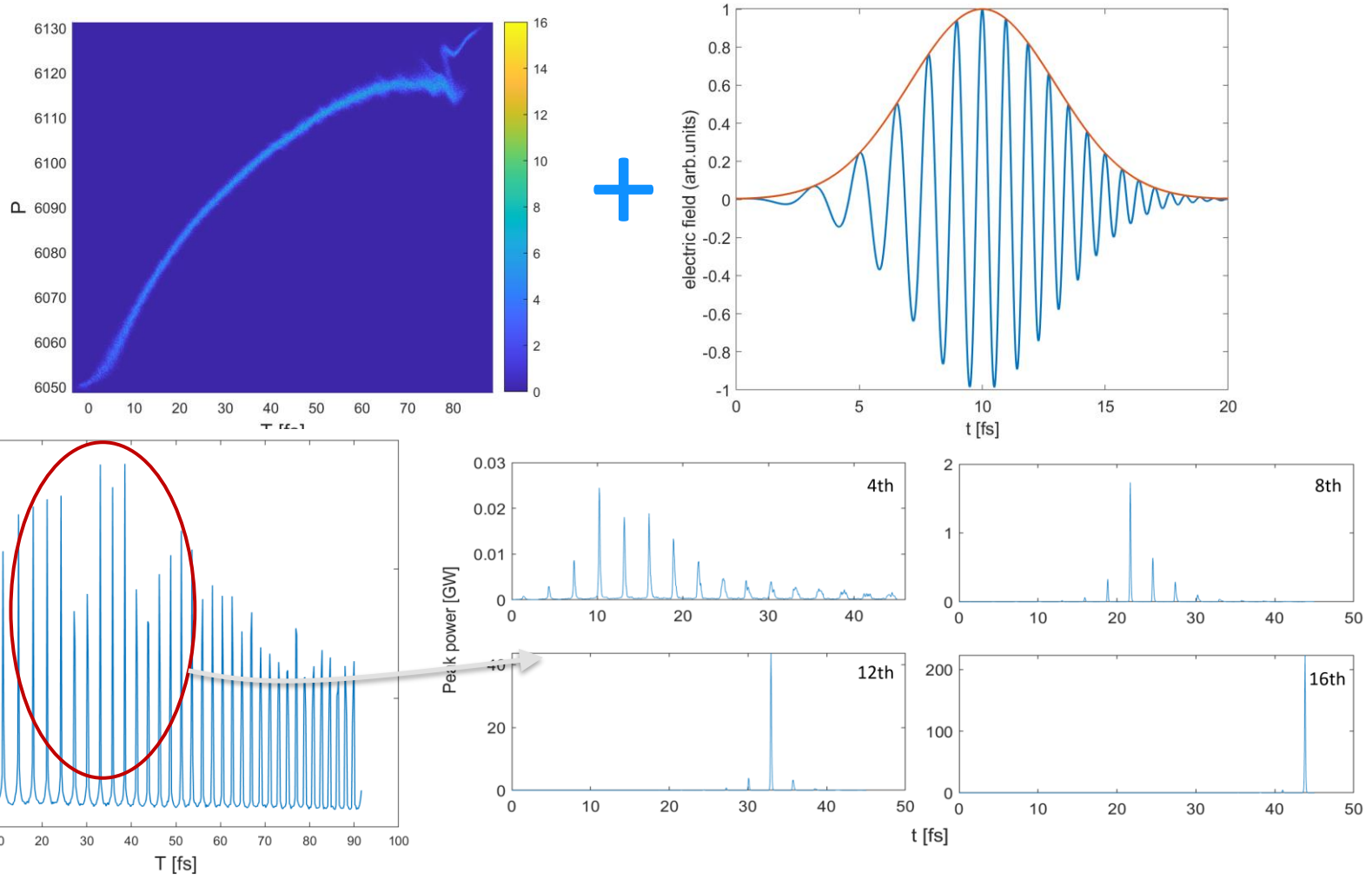
- E-SASE to enhance the local beam current, e.g. 2kA to 12 kA in Athos
- Using beam energy chirp and seed laser chirp to generate uneven separation of current spikes
- Multi-stage amplification to amplify one short FEL pulse



- 1st: simulations and specify laser requirements
- 2nd: experimental demonstration

Outlook: fresh-slice multi-stage amplification with ESASE

- Using beam energy chirp and seed laser chirp to generate unequal current distribution
- Controlling the number of current spikes by dispersion tilt
- Results for 16 amplification stages (1 module in each): ~200 GW and ~250 as (FWHM)



Conclusion

1. Demonstrated fresh-slice multi-stage amplification scheme in Athos with beam tilt
2. Efficient amplification with up to 4 stages
3. Pulses with mJ energies and few fs duration for 0.5 and 1 keV
4. Mode already used in Athos (data under analysis)
5. Outlook: MSA amplification with ESASE

PAUL SCHERRER INSTITUT

PSI

Thank you !