PAUL SCHERRER INSTITUT

Philipp Dijkstal :: FEL Beam dynamics :: Paul Scherrer Institut

Electron beam manipulation using self-induced fields

LEDS2023 - Longitudinal Electron beam Dynamics for coherent light Sources - Frascati, Oct 3-5, 2023

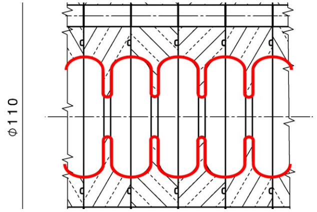
Contents

1) Surface wakefields
   - Beam tilt generation and chirping or dechirping.
   - Electron beam and FEL power profile shaping using transverse wakefields
     - Reversible control of the FEL performance of a longitudinal slice
     - Multi-stage amplification of a short FEL pulse
   - Current profile shaping using longitudinal wakefields
     - As alternative to higher-order linearizer cavities
     - Multi-current horn generation
2) Space charge and CSR wakefields

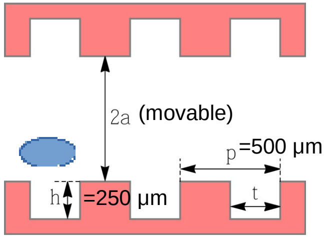
Surface wakefields for tilt generation and dechirping

Use wakefields generated by dedicated devices, or whichever source is available, for diagnostics (next talk by Alexander Malyzhenkov), or longitudinal or transverse beam shaping (this talk).

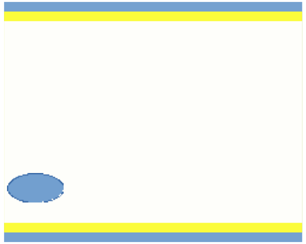
Drawing of a C-band rf cavity



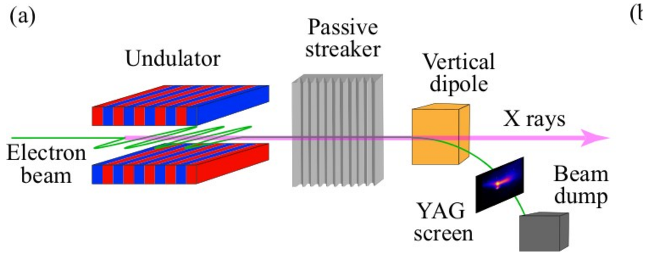
Corrugated structure



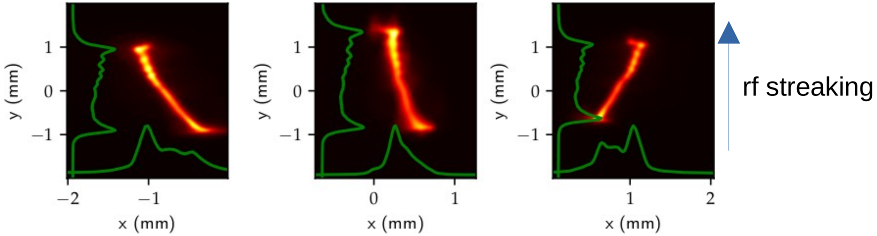
Dielectric structure

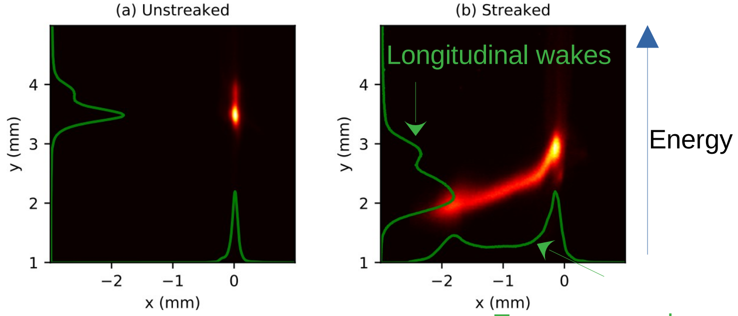


Beam on a dispersive screen after the SwissFEL Aramis passive streaker.



Beam tilt generated by moving the beam off-axis in an rf cavity. Tilt is surprisingly linear.



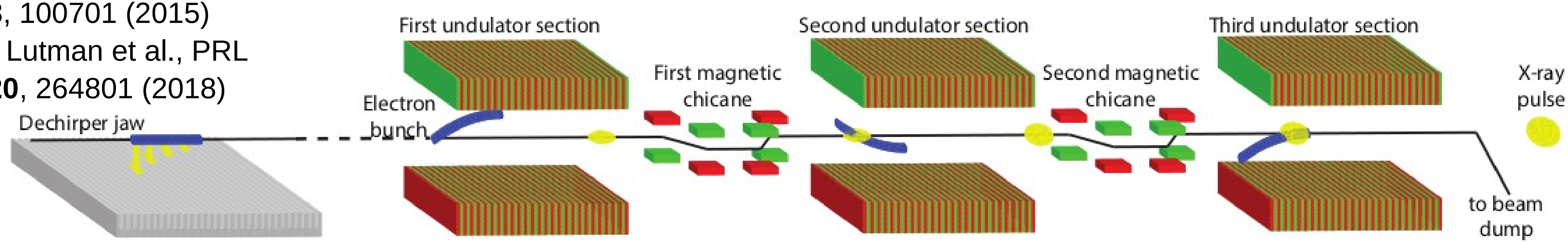


P. Dijkstal, PhD thesis, https://doi.org/10.3929/ethz-b-000576424

P. Dijkstal et al., Phys. Rev. Res. **4**, 013017 (2022)

Control over the lasing slices in an FEL through transverse wakefields

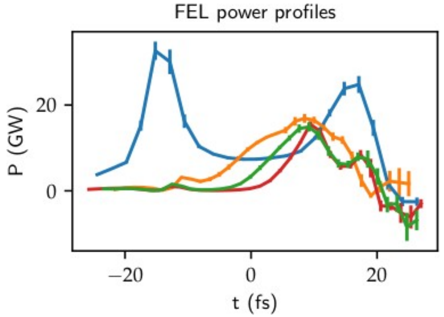
E. Prat et al., PRST-AB **18**, 100701 (2015)
A. Lutman et al., PRL **120**, 264801 (2018)



- Beam tilt: reversible suppression of the FEL process in most slices through orbit oscillations in the undulator section.
- Contrary to irreversible methods (slotted foil, cathode laser spoiler), this allows for re-amplification of the FEL pulse in stages, leading to higher power.
- Alternatively, one can use a single stage. Routinely done at Aramis, where there are no delaying chicanes. Some users however are not fully satisfied with the transverse quality of the FEL pulses generated with tilted beams.
- For short pulses from a single stage, the FEL suppression does not have to be reversible which allows for many different methods.
- Maybe a variable charge scheme would be better, or laser heater shaping. But this is also more work to set up (and more difficult with double-bunch operation).

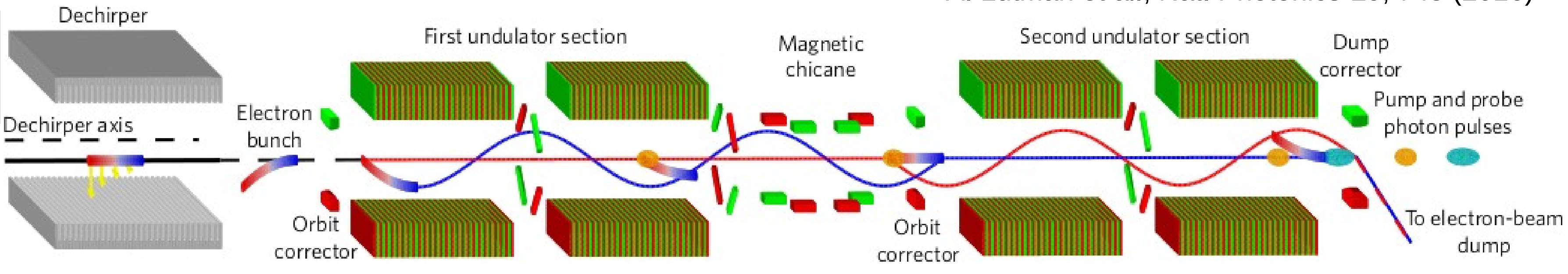
Tunable duration at SwissFEL Aramis:

P. Dijkstal, PhD thesis, https://doi.org/10.3929/ethz-b-000576424



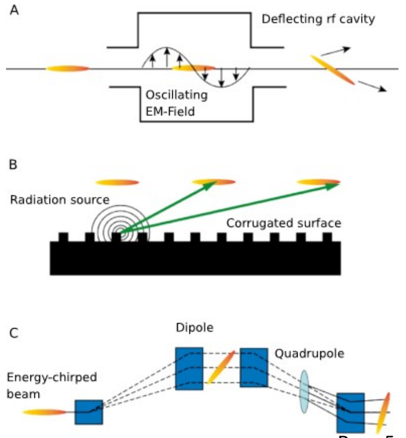
Now with two-color FEL generation

A. Lutman et al., Nat. Photonics **10**, 745 (2016)



- Same idea as last slide, except that a new FEL pulse is generated in the second stage, instead of amplifying the same FEL pulse.
- Instead of from wakefields, tilt can also be generated with dispersion. This requires a linear energy chirp.
- Done at Athos, the soft X-ray beamline at SwissFEL.
  - Two-color: E. Prat et al., Phys. Rev. Res. **4**, L022025 (2022).
  - Fresh slice multi-stage amplification: G. Wang et al., manuscript in preparation.
- In principle, tilt can also be generated with TDS, but for FEL pulse shaping this gave very poor results at SwissFEL Aramis: P. Dijkstal et al., Proc. FEL 2022, MOP51.

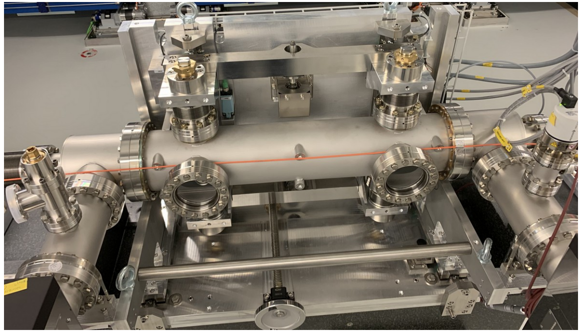
Methods of beam tilt generation

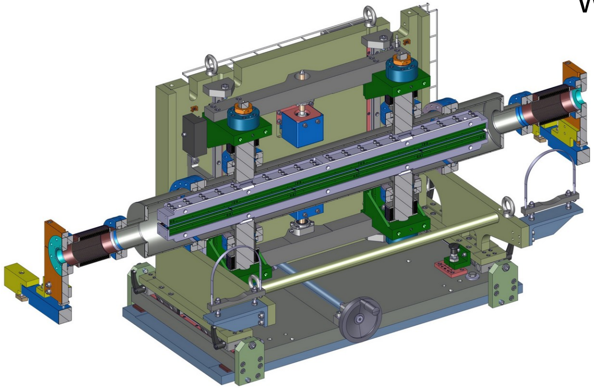


Hardware: corrugated structures

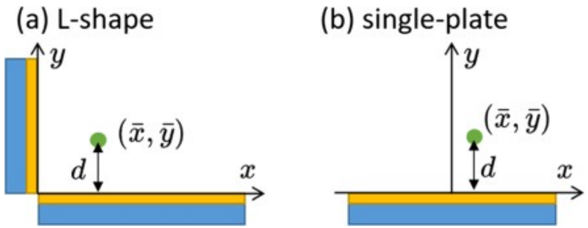
- For dechirping, the beam passes through the center of a symmetric (i.e., round or double-sided structure). The gap should be adjustable to control the strength of the dechirping.
- For tilting, one corrugated plate is enough. To control the streaking strength, can either move the plate towards the beam, or move the beam towards the plate. This means it is possible to use a non-movable structure, as done at European XFEL for diagnostics.
- To cancel quadrupole (transverse focusing or defocusing) effects:
  - Use two structures that have different orientations (one horizontal, one vertical).
  - For streakers, can use an L-shaped structure as done at European XFEL for beam shaping.

PSI double-sided movable corrugated passive streaker:
P. Dijkstal et al., Proc. IPAC 2023, THPL153





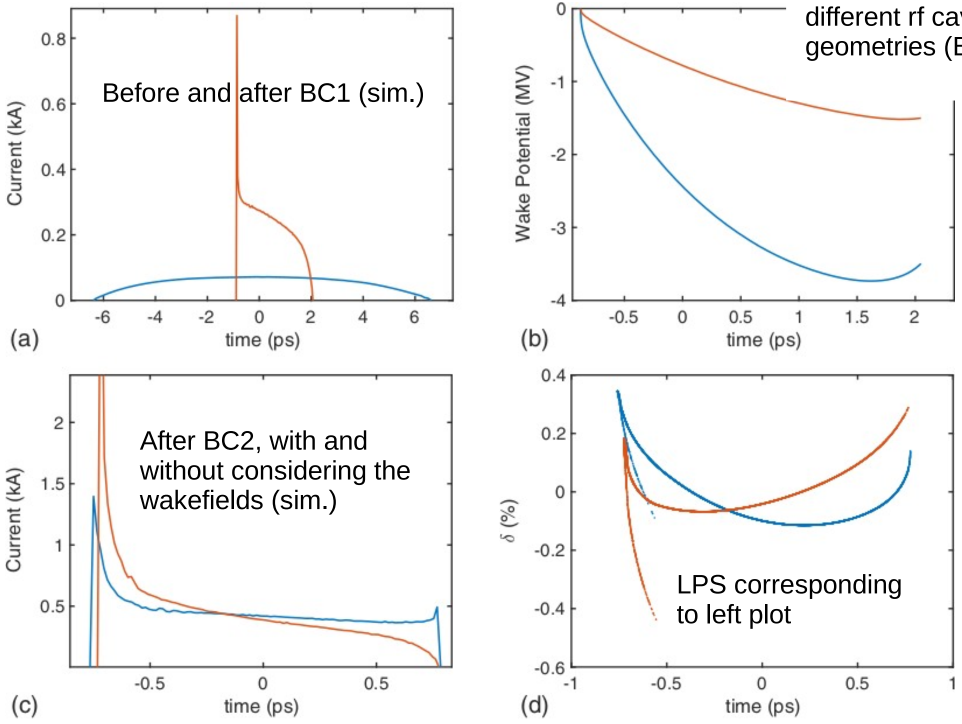
Analytical and numerical wakefield calculations:
W. Qin et al., PRAB **26**, 064402 (2023)



Current profile manipulation with wakefields

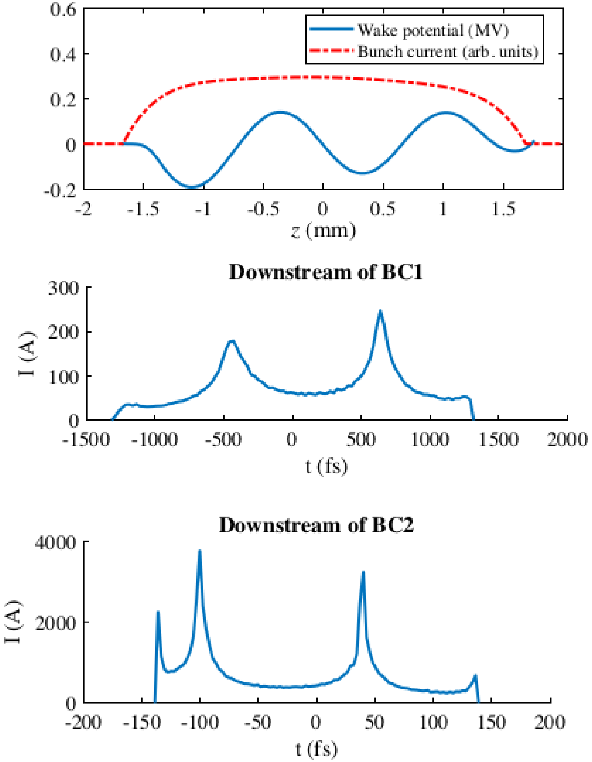
Wakefields from rf cavities linearize the phase space at FERMI

Wakefields assuming two different rf cavity geometries (BTW or TW)



G. Penco et al., PRL **119**, 184802 (2017)

Current profile manipulation



S. Bettoni et al., PRAB **21**, 082801 (2021)

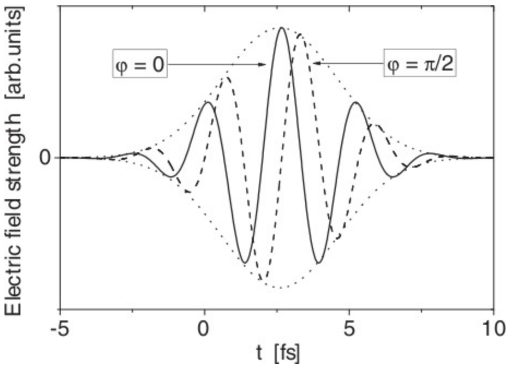
Contents

1) Surface wakefields
2) Space charge and CSR wakefields
   - The Chirp/Taper method of ultra-short FEL pulse generation.
   - XLEAP at LCLS: attosecond FEL pulse generation
     - CSR from the tail current horn
     - Photo-cathode temporal shaping
     - Laser heater temporal shaping
   - ASPECT project at European XFEL
   - First experimental results of photo-cathode temporal shaping at SwissFEL

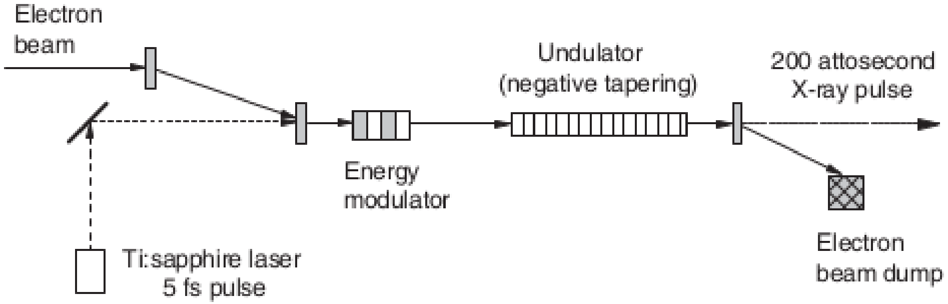
The Chirp/Taper method of short FEL pulse generation

- For a constant linear energy chirp along the beam, the FEL resonance condition can be upheld via a linear taper of the undulator K values.
- Conversely, if the energy chirp variations along the bunch are sufficiently large, then the lasing part can be selected through the appropriate choice of undulator taper.
- Original idea proposed by E. Saldin et al, PRST-AB **9**, 050702 (2006): generate a strongly varying chirp with an ultra-short external laser pulse in a modulator. But such lasers are expensive / could not be built until recently.
- Solution: use self-modulation forces to generate the chirp.

Ultra-short external laser pulse.



Proposed experimental setup.



Resonance condition in presence of a linear chirp

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

Self-modulation methods for generation of sub-fs pulses at LCLS

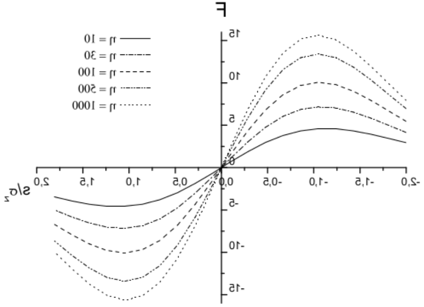
- XLEAP project is a huge success at LCLS: towards the end of the LCLS-I era, ~50% of soft X-ray user beam time used sub-fs pulses provided by XLEAP.
- All methods have in common that most of the modulation is done by forces generated by the beam itself. External lasers are employed, but these are the photocathode and laser heater optical lasers which are standard at X-ray FEL facilities.
- The self-modulation forces are longitudinal space charge and CSR. They are amplified by R56 from chicanes and doglegs, or by the magnetic forces in wigglers and undulators
- In summary, relatively little investment is required for a high impact.
- Three methods, all discovered and first demonstrated at SLAC under leadership of A. Marinelli:
  - First method: Long-range CSR self-modulation in wiggler:
    J. Duris et al., Nat. Photonics **14**, 30 (2020).
  - CSR method was quickly superseded by photocathode temporal shaping:
    Z. Zhang et al., New. J. Phys. **22**, 083030 (2020).
  - Next idea: laser heater temporal shaping, so far only in simulations:
    D. Cesar et al., PRAB **24**, 110703 (2021).

Self-modulation forces are enhanced in wigglers or undulators

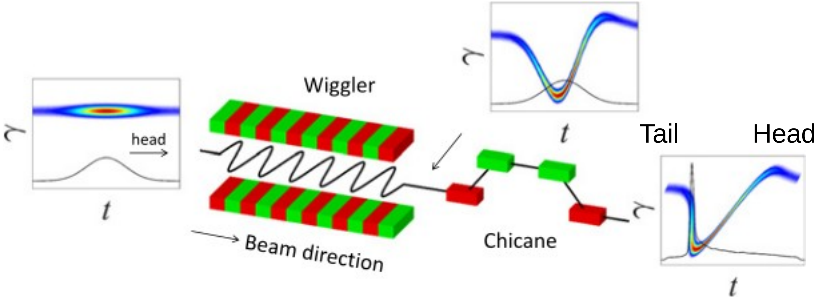
- Long range CSR: a sharp current spike (which can have low beam quality) modulates preceding region with high beam quality.
- Short range CSR or space charge: a current spike with good beam quality modulates itself.
- The energy modulation (chirp) is compressed with a chicane.
- R56 should ideally be positive to compress SC, can have either sign for CSR.
- Can also use first undulators to generate more chirp if there is a sharp current spike.

Space charge in undulators: G. Geloni et al., arXiv: 0706.2280v1 (2007).

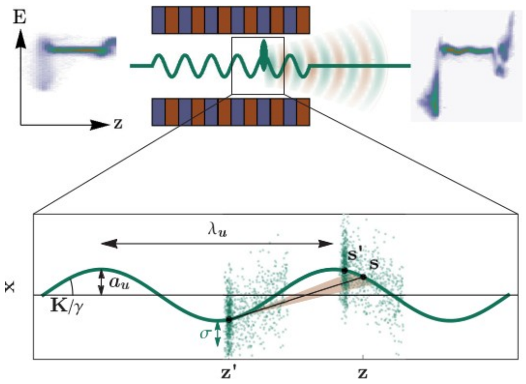
Flipped axis for consistency.



Short range CSR: Z. Zhang et al., New. J. Phys. **22**, 083030 (2020)



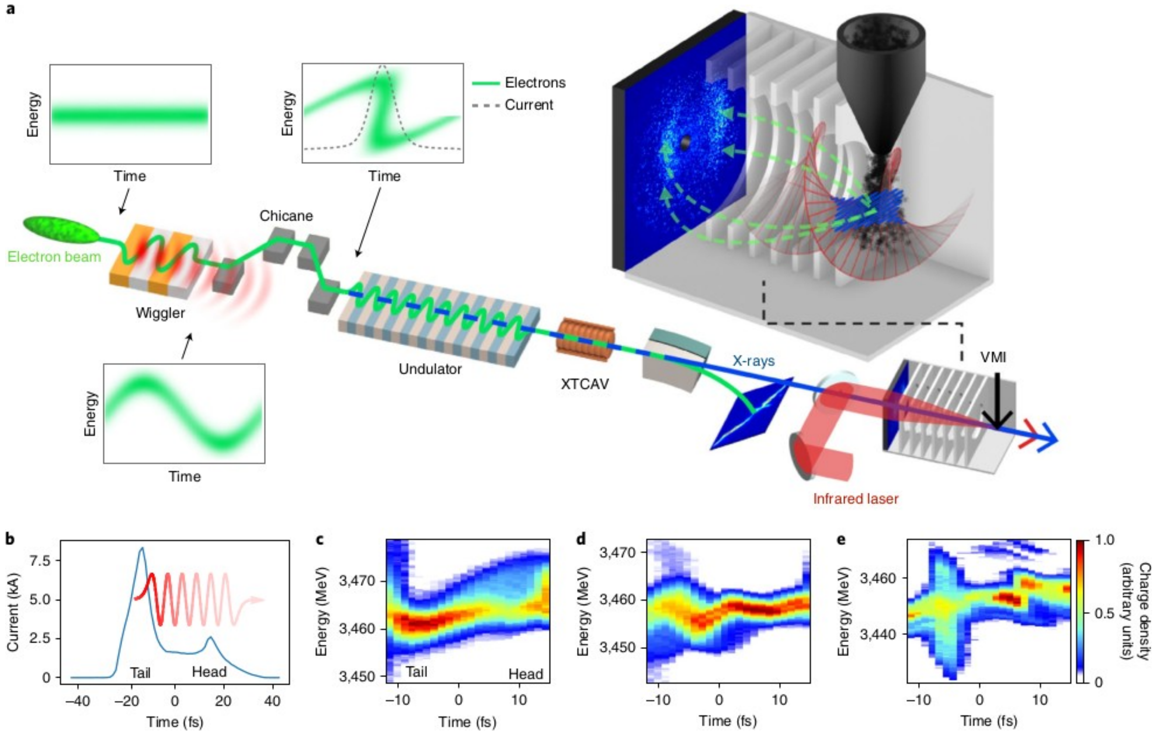
Long range CSR: J. MacArthur et al., PRL **123**, 214801 (2019)



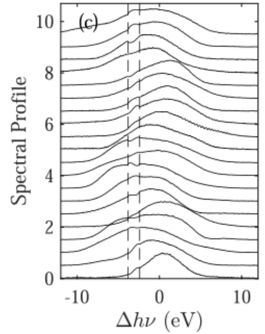
Short-range CSR method CSR method continued

- Modulation station in front of soft X-ray undulator section at LCLS, consisting of wiggler and chicane.
- By now, in total 4 modulators are installed.
- CSR method superseded by photocathode temporal shaping, see next slide.
- Short pulse durations confirmed with angular streaking, but that is not essential for the method.

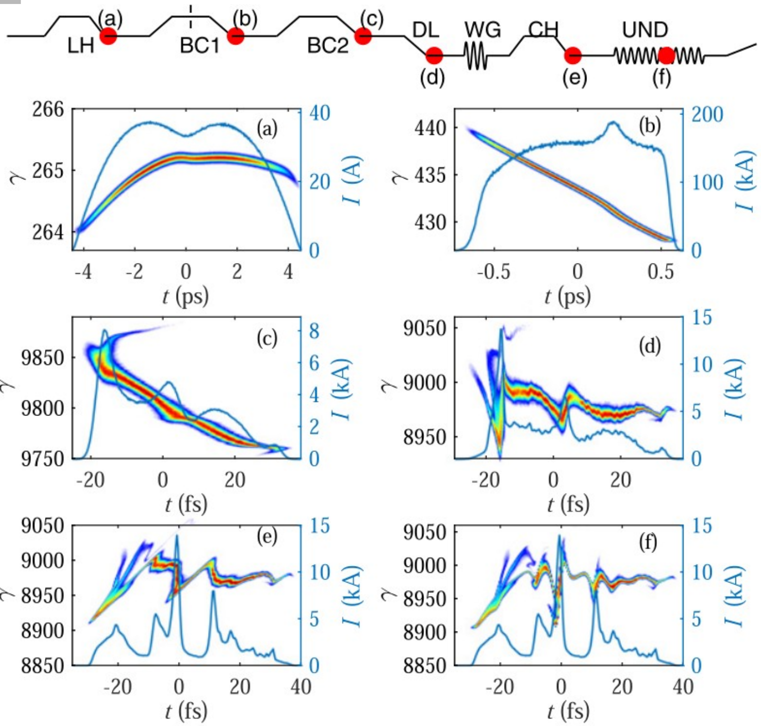
J. Duris et al., Nat. Photonics **14**, 30 (2020)



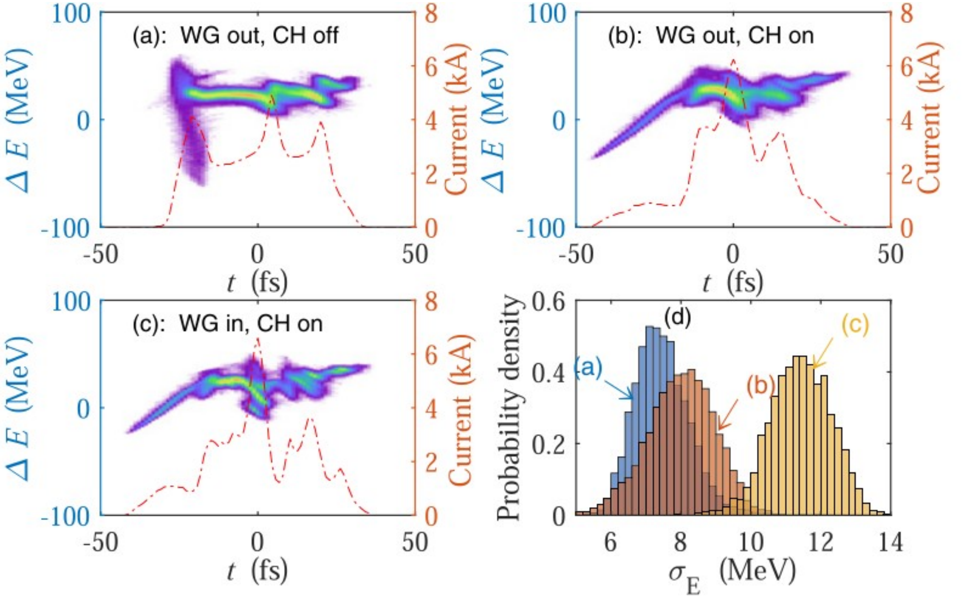
Photocathode temporal shaping



Simulations



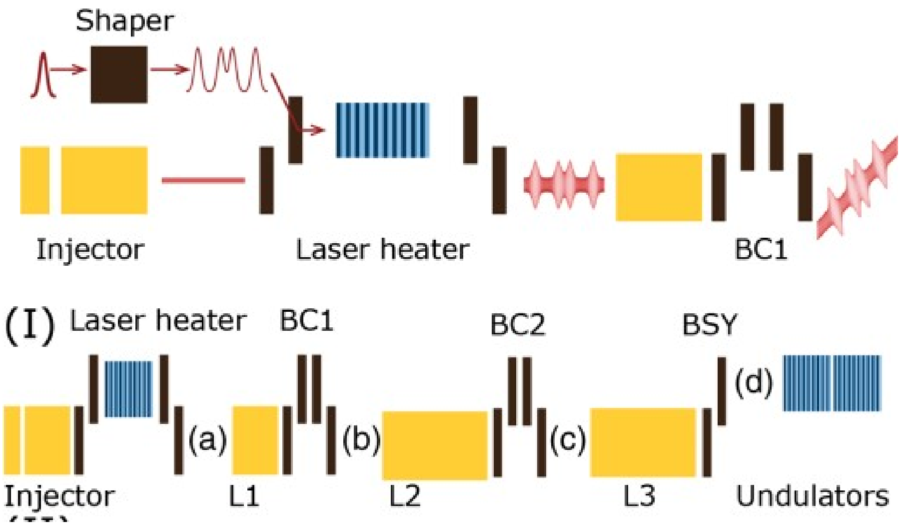
Measurements



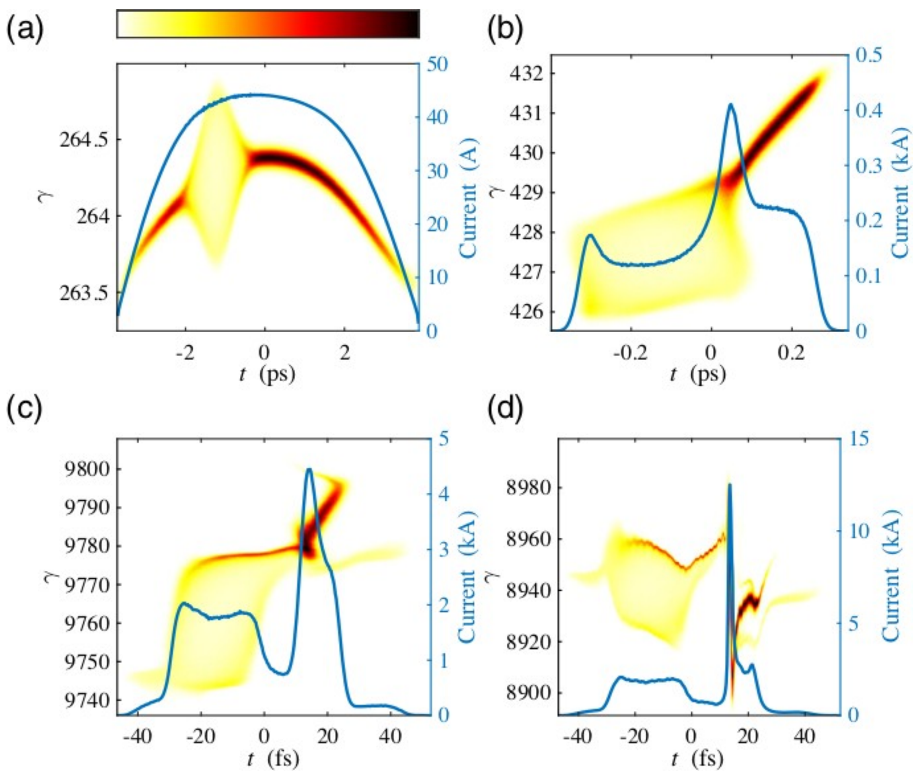
Z. Zhang et al., New. J. Phys. **22**, 083030 (2020)

Laser heater temporal shaping

- This time, the initial disturbance is introduced at the LH instead of the cathode.
- Very promising simulations.
- Demonstration of this mode not yet achieved.
- Many other use cases of LH shaping are explored in this reference:
  - Multi current spikes.
  - FEL pulse train.
  - Current horn suppression.



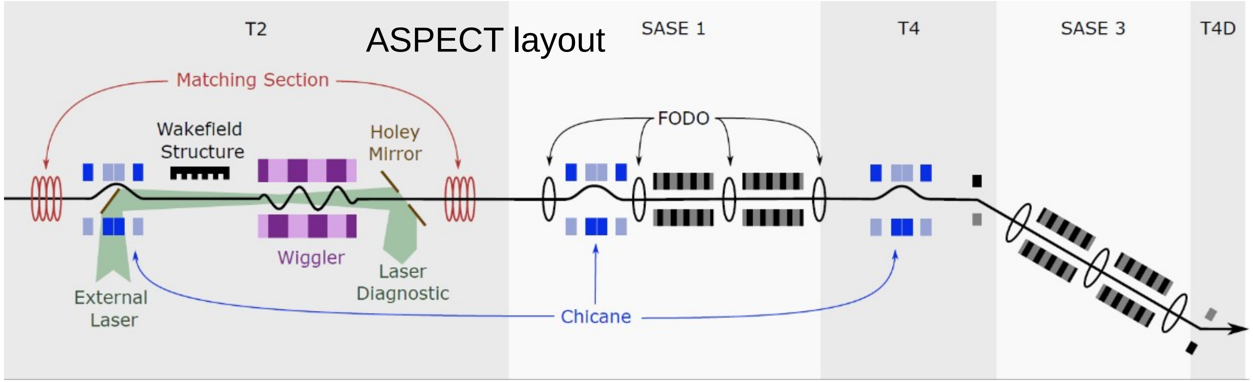
D. Cesar et al., Phys. Rev. Accel. Beams **24**, 110703 (2021)



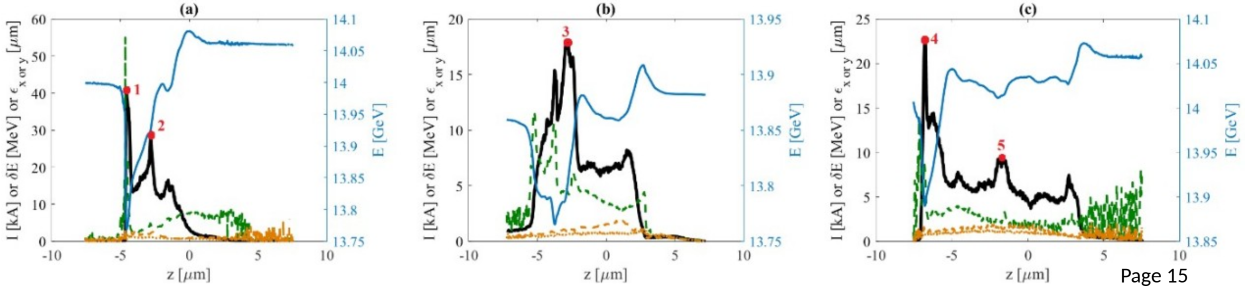
ASPECT, the ongoing project for generation of sub-fs pulses at European XFEL

- Atto-Second Pulses from ESASE and Chirp / Taper.
- From machine side: G. Geloni and M. Guetg (project leaders), J. Yan, Y. Chen, C. Lechner, E. Schneidmiller.
- Modulation station with L-shaped streaker (separate project by W. Qin), external laser + modulator, and chicanes.
- Main goal: sub-fs pulse generation in SASE1 and SASE3 after direct phase space modulation from external laser.
- Alternative, laser-less methods: 1. photocathode temporal shaping and 2. only compression settings.

ASPECT layout

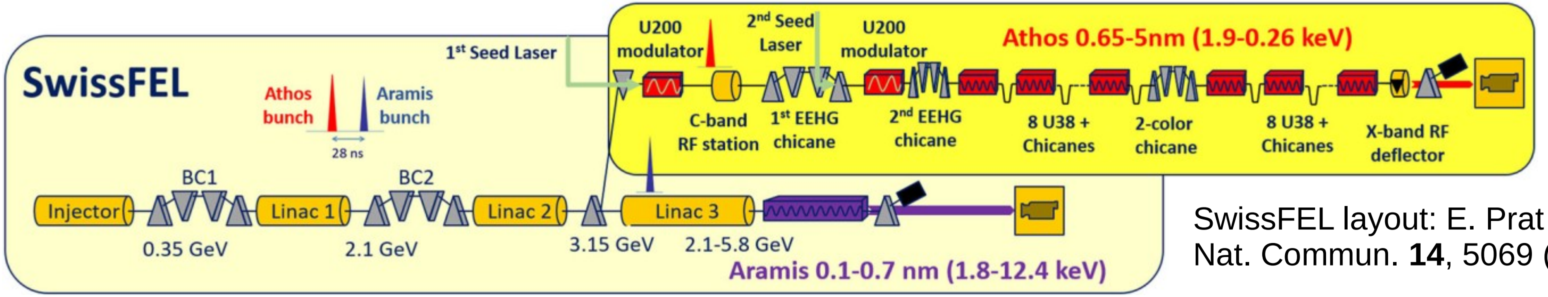


Photocathode temporal shaping: S2E simulations by Ye Chen (DESY), using OPAL code



Ongoing photocathode temporal shaping project at SwissFEL

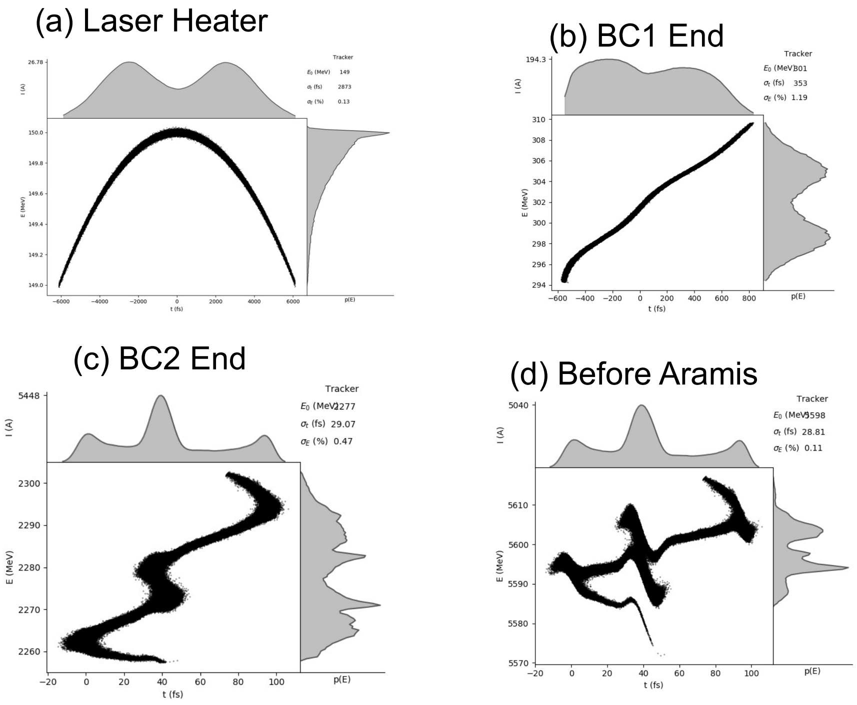
- Arrival of new postdoc Zhaoheng Guo at PSI, before a PhD student at SLAC and part of the XLEAP team, gave impetus to try photocathode temporal shaping.
- Gun laser group (A. Trisorio, C. Vicario et al.) was very supportive from the start.
- Long-term plan: deliver sub-fs pulses to either beamline, or simultaneously to both beamlines.
- Development ongoing:
  - We try first to realize the scheme at Aramis, then at Athos.
  - We initially use both our gun lasers in the same rf bucket for the photocathode temporal shaping.
  - We later want to use a split-and-delay unit to require only one laser. Before that we need to figure out the optimal delay.
- Energy Collimator before Aramis (not shown) and Switchyard before Athos can have positive R56.



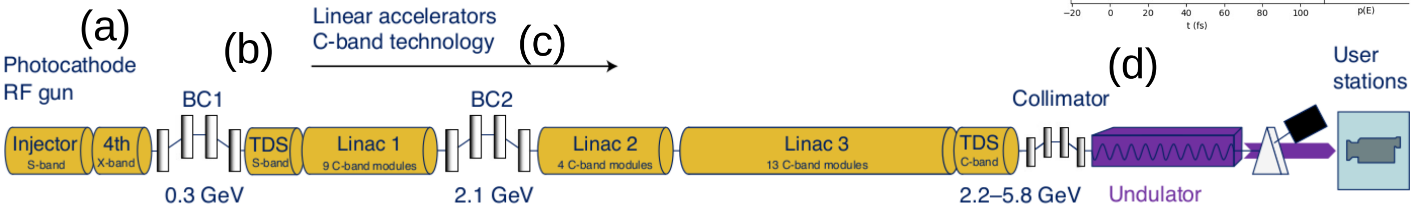
SwissFEL layout: E. Prat et al., Nat. Commun. **14**, 5069 (2023)

First coarse numerical study of photocathode temporal shaping at SwissFEL Aramis

- BC1 and BC2 generate a current spike at the center of the bunch, up to 4~5 kA.
- After BC2, the space charge effect enhances the energy chirp within the spike.
- The current spike is compressed in the Energy Collimator (usually isochronous), which requires a R56 > 0 (not simulated here).
- Simulations done by Zhaoheng with 2D tracking code by A. Rutschmann.

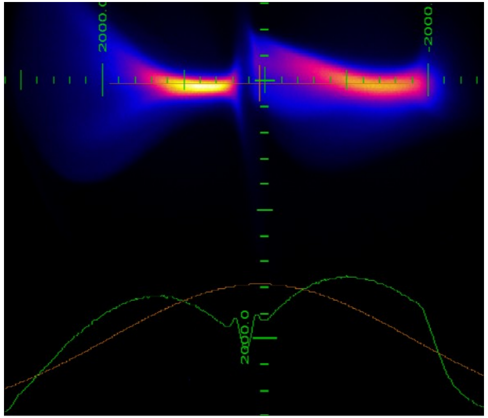


SwissFEL Aramis layout: E. Prat et al., Nat. Photonics **14**, 748 (2020)

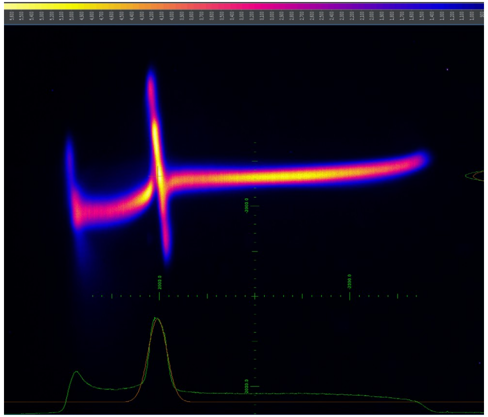


Results from first shift (Dijkstal, Guo, Prat, Trisorio, Vicario)

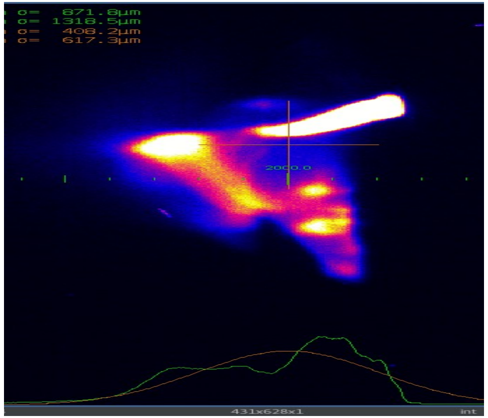
Current profile after BC1 (TDS)



LPS in ECOL (TDS)



LPS After Aramis (passive streaker, non-monotonic wake potential)

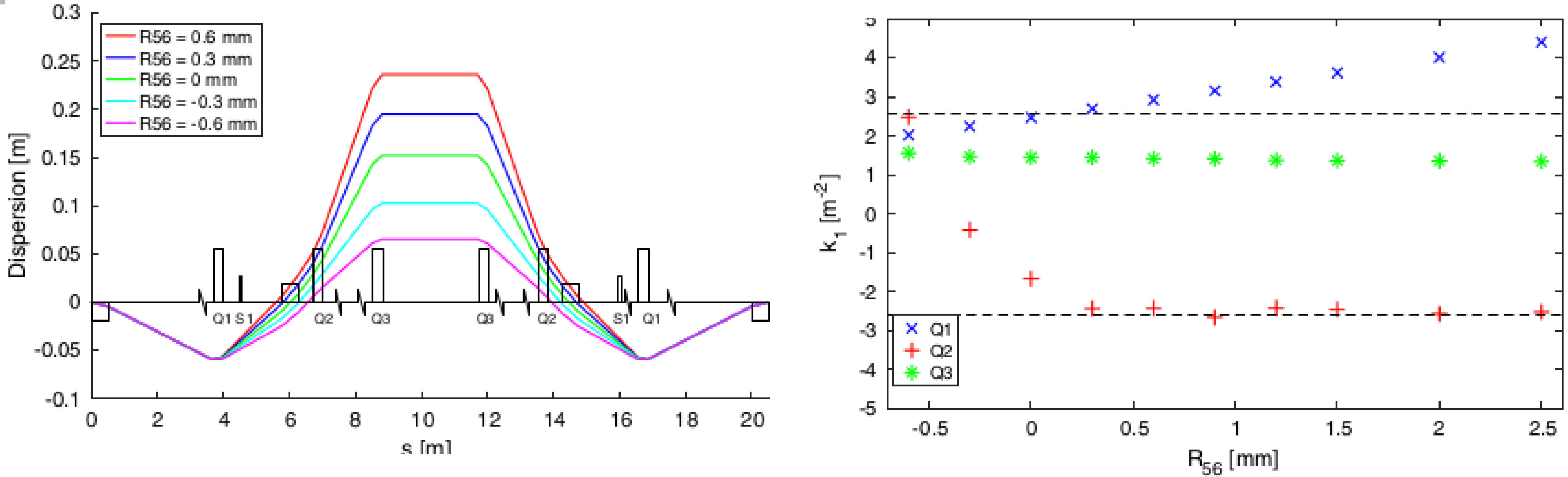


Status after first shift:

- Principle of photocathode shaping (both gun lasers in the same rf bucket) was demonstrated: we see a disturbance in the current profile that is later amplified into a current spike at the center of the bunch.
- We work at a different gun phase: at max energy instead of min energy spread. Seems to work (low slice emittance maintained at the core) but not clear if that is the best way. Astra simulations of the gun might be needed.
- Next steps: positive R56 at the ECOL and generation of short pulses in Aramis with Chirp/Taper. Try Athos.
- Not understood yet: reason for "hole" in current profile after BC1.

Aramis ECOL R56 tunability

Á. Saá Hernández et al., Phys. Rev. Accel. Beams **22**, 030702 (2019)



- Aramis ECOL R56 tunability was previously studied for an unrelated project. The tunability is limited by quadrupole strength.
- Need to reduce beam energy to ~4 GeV to reach positive R56, which is needed to convert space charge chirp to a single current spike.

Summary

- Effects that are usually detrimental and undesirable (Wakefields, CSR, Space Charge) can and should be used for beam shaping wherever suitable.
- Wakefields
  - … from dedicated devices or simply from e.g. the rf cavities are useful for chirp control, FEL pulse duration control, two-color FEL, compression linearization, ...
  - In combination with beam delaying chicanes, they can be used for fresh-slice multistage FEL amplification.
  - Hardware: flat or L-shaped, double-sided or single-sided, movable or non-movable, dielectric or corrugated.
- CSR and Space Charge
  - … within a dedicated modulation station (modulator + chicane) can replace an external laser by using the tail current spike (“horn”) to modulate the central part of the electron beam.
  - … along the linac can amplify initial LPS irregularities introduced in the gun or at the laser heater into large variations at the undulator entrance.
  - Hardware:
    - Wigglers (permanent or electromagnets).
    - Chicanes / doglegs with positive R56 to convert SC chirp to a current spike, or with either sign of R56 to convert CSR chirp to a current spike.

Thank you for your attention.