Self-locked time-resolved measurements with a passive streaker

Alexander Malyzhenkov, Philipp Dijkstal, Eduard Prat

LEDS2023 Workshop
Frascati, Italy
October 4, 2023

Outline

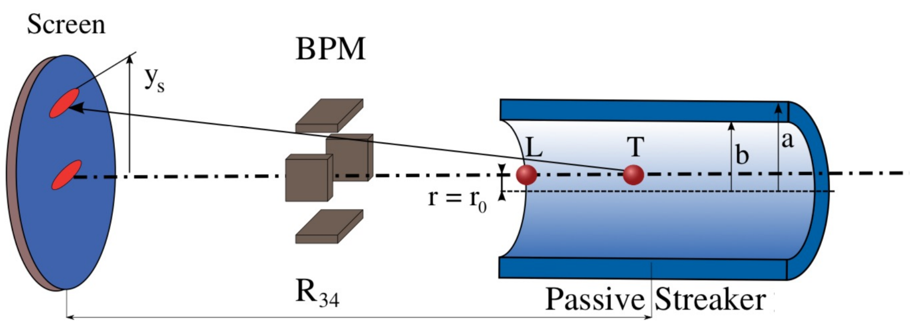
1. Introduction to the method
2. Review of the results at SwissFEL (PSI)
3. Brief look into the results at EXFEL (DESY)
4. Development of the new device for CLEAR (CERN)
5. Conclusion & next steps

Introduction to the method

Time-resolved diagnostics of electron beam with passive structure

Idea:

- Electron beam moving off-axis excites strong transverse wakefields in a corrugated or dielectric structure
- Wakefields give a time-dependent transverse kick to the electrons
- This allows to resolve the time profile of the e-beam on the screen



Experimental demonstration at SwissFEL Injector Test Facility (dielectric structure): S. Bettoni et al., PRAB **19**, 021304 (2016)

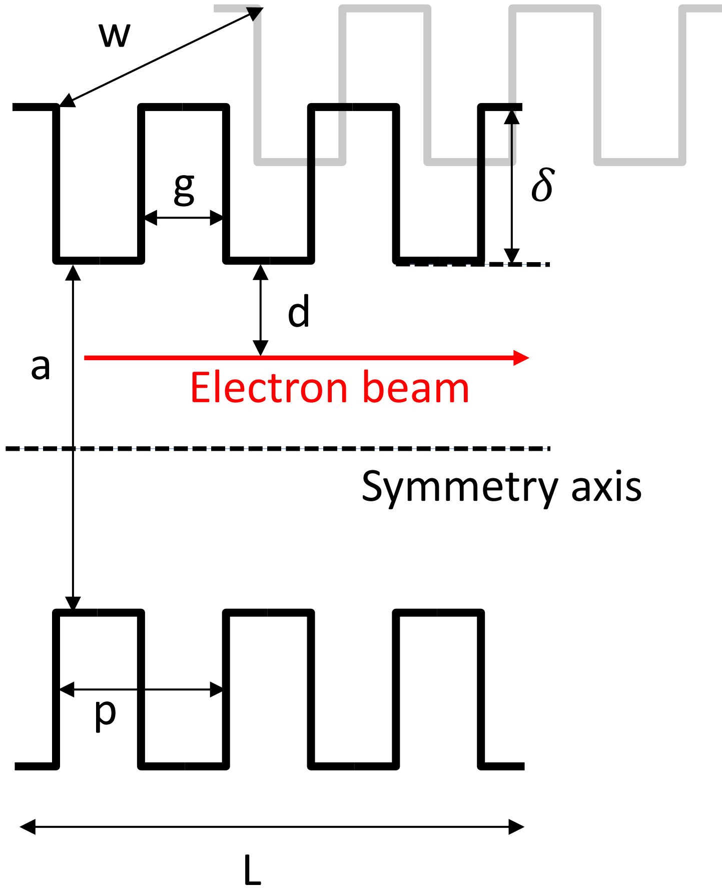
Advantages:

- Cheap and simple: manufacture and operation (self-driven)
- Self-locked: no RF phase or arrival time jitter effects

Disadvantages:

- Head is not resolved
- Orbit jitter sensitivity
- Nonlinear streaking: reconstruction is sophisticated

Geometric parameters of the corrugated passive structure (example for SwissFEL structure)



Fixed parameters:

- δ = 250 μm (corrugation depth)
- p = 500 μm (period)
- g = 250 μm (longitudinal gap)
- w = 10 mm (plate width)
- L = 1 m (length of the structure)

Variable parameters:

- a = variable gap (typically 6 -10 mm)
- d = offset (beam distance to the jaw)

Transverse and Longitudinal wakefield models for this geometry is very well developed!
For example: Bane, Stupakov and Zagorodnov: PRAB 19, 084401 (2016)

Wakefield model (dipole approximation)

Single-particle transverse wakefield (from PRAB 19, 084401, 2016):

$$w_{xd}(s,\mathrm{x}) \approx \frac{Z_0 c}{4\pi}\frac{\pi^3}{4a^3} sec^2\left(\frac{\pi x}{2a}\right)\tan\left(\frac{\pi x}{2a}\right) s_{0yd}\left[1-\left(1+\sqrt{\frac{s}{s_{0d}}}\right)e^{-\sqrt{\frac{s}{s_{0d}}}}\right]$$

Unit: V/C/m

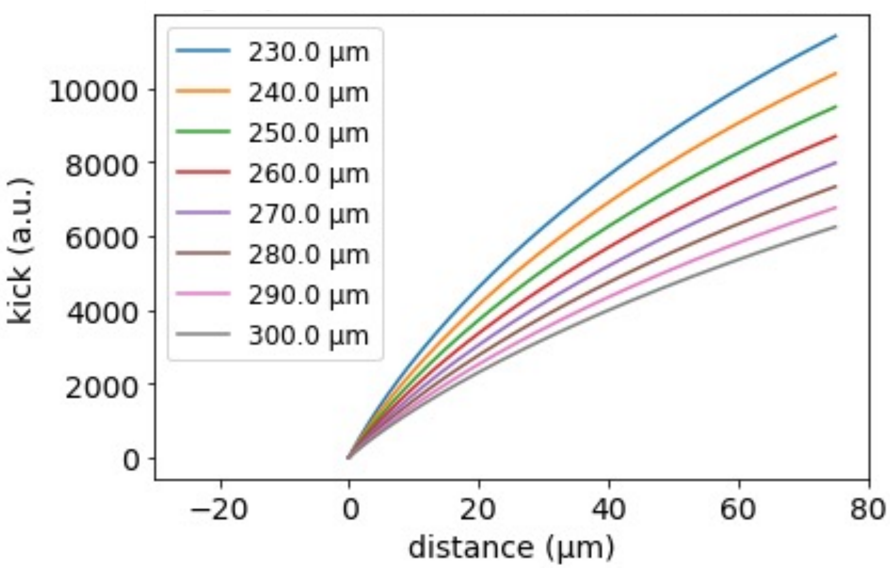
Equivalent distance scale factor:

$$s_{0yd}(\mathrm{x}) = 4s_{0r}[\frac{3}{2}+\frac{\pi x}{a}\csc\left(\frac{\pi x}{a}\right)-\frac{\pi x}{2a}\cot\left(\frac{\pi x}{a}\right)]^{-2}$$

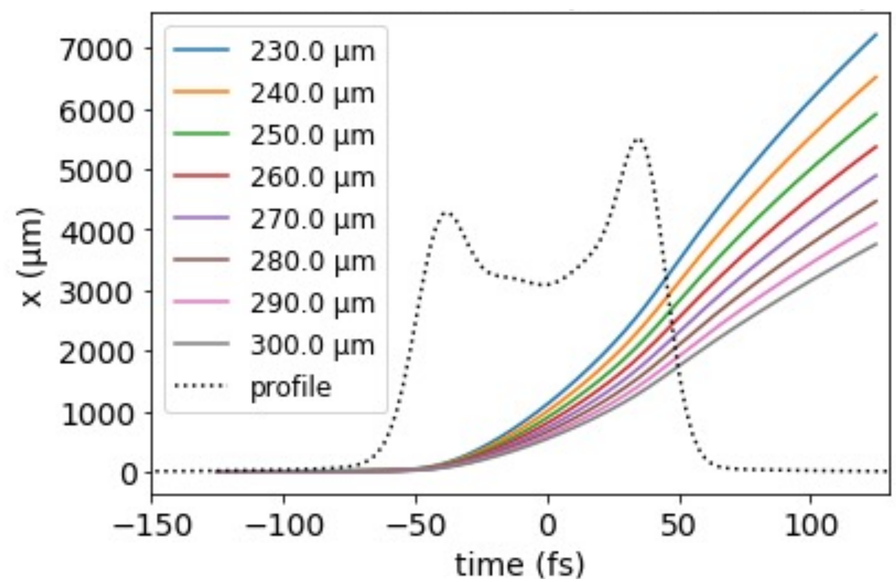
Distance scale factor [m]:

$$s_{0r} = \frac{a^2\delta}{2\pi\alpha^2 p^2}$$

Single-particle wake (200 pC bunch)



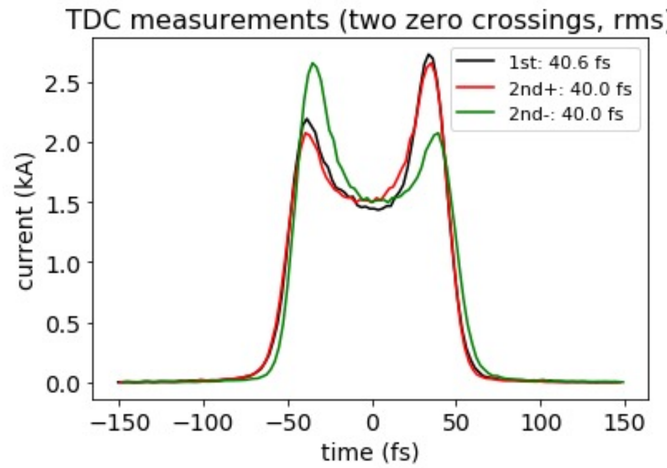
Offset from the convolved wakefield kick

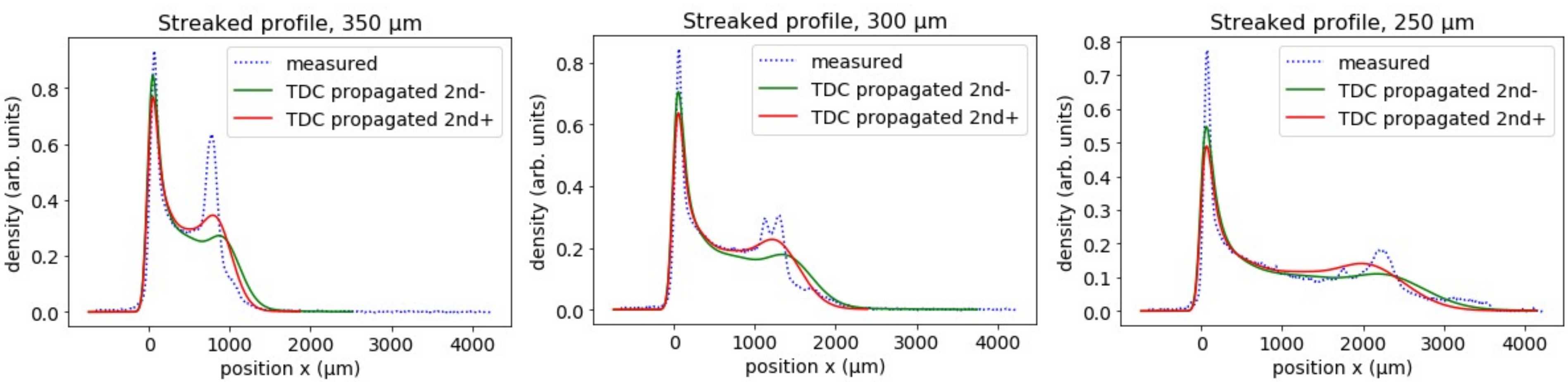


Predictions and measurements for the passive streaking

Benchmarking the model:

- Measure current profile with transverse deflector
- Calculate transverse wakefield kick by convolving single particle wake with current profile
- Using the calculated offset at the screen, map the current profile to the measurement screen including the screen resolution and natural beam size
- Repeat the procedure for different offsets
- Compare with measurements



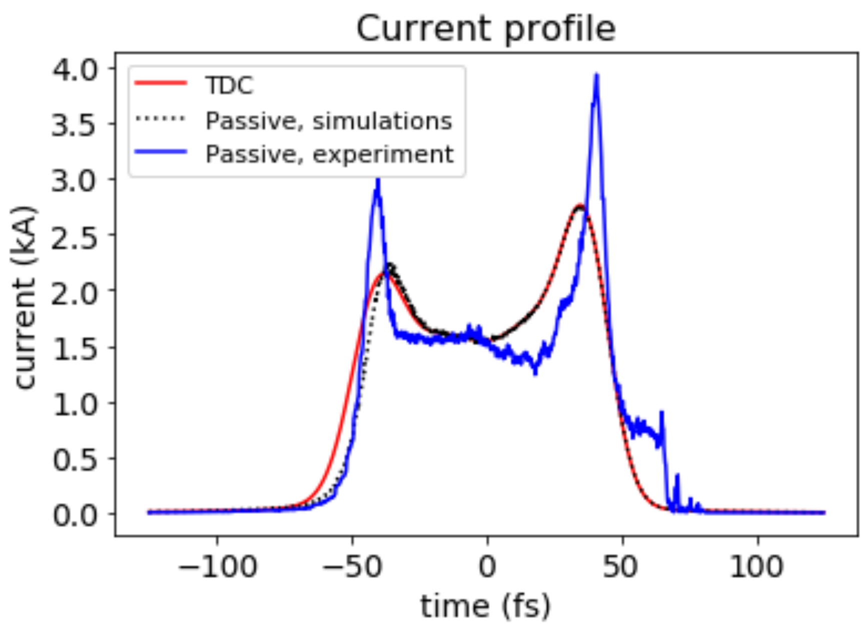


(The results are from the actual first measurements at SwissFEL in 2020)

Reconstruction of the current profile with TDC-based calibration

Strategy:
- Calculate wakefield mapping for the current profile measured with TDC (2 slides ago)
- Use it to back-propagate the measured distribution to the time domain

- Why is it useful:
  - Cross-check the model
  - Reconstruct time-resolved properties of the bunch downstream the TDC



- Single shot
- Max streak

(The results are from the actual first measurements at SwissFEL in 2020)

Time-resolved diagnostics of photon beam from electron beam for XFELs

Two signatures of an FEL process:

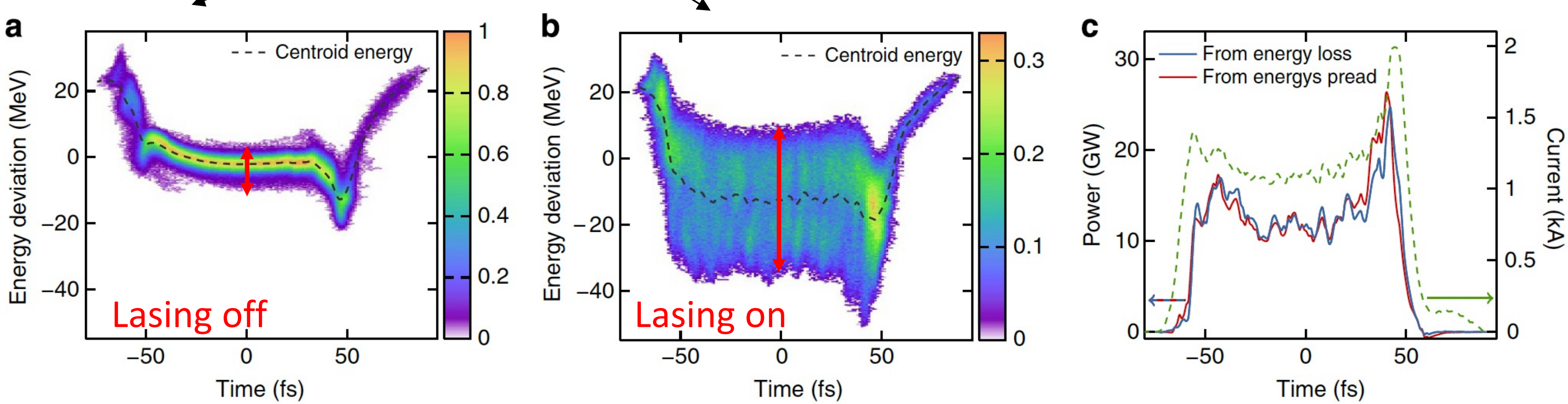
- electrons lose energy (emitted with X-ray)
- the slice energy spread of the lasing part increases

$$P_{c.e.} = I(E_{off} - E_{on})$$

$$P_{e.s.} \sim I(t)^{2/3} * (\sigma_{on}{}^2 - \sigma_{off}{}^2)$$

Idea: measure the FEL-induced lasing effects imprinted on the electron beam longitudinal phase space: Y. Ding et al., PRAB 14, 120701 (2011)

Post-undulator measurements are required



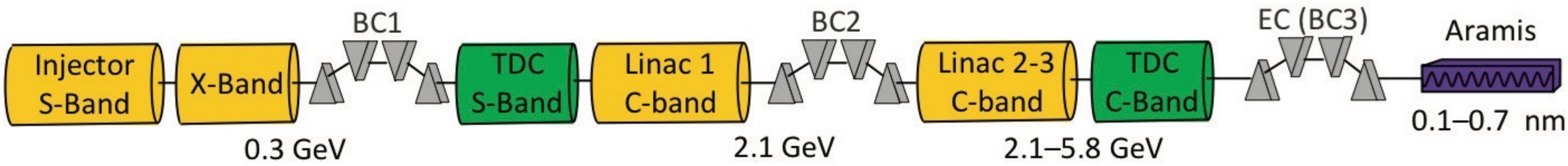
First experimental demonstration at LCLS with X-band active deflector:
C. Behrens et al., Nat. Communications **5**, 3762 (2014)

Method should also work with a passive deflector instead of an active one!

Review of the results at SwissFEL (PSI)

Standard time-resolved diagnostics at SwissFEL: Hard X-ray brunch Aramis

Time-resolved diagnostics of electron and photon beams are essential for the FEL performance and user's experiments!



Electron beam:

- Measuring electron beam current profile and longitudinal phase space (in the dispersive sections) with S-band and C-band transverse deflecting cavities (TDC) before the undulator entrance

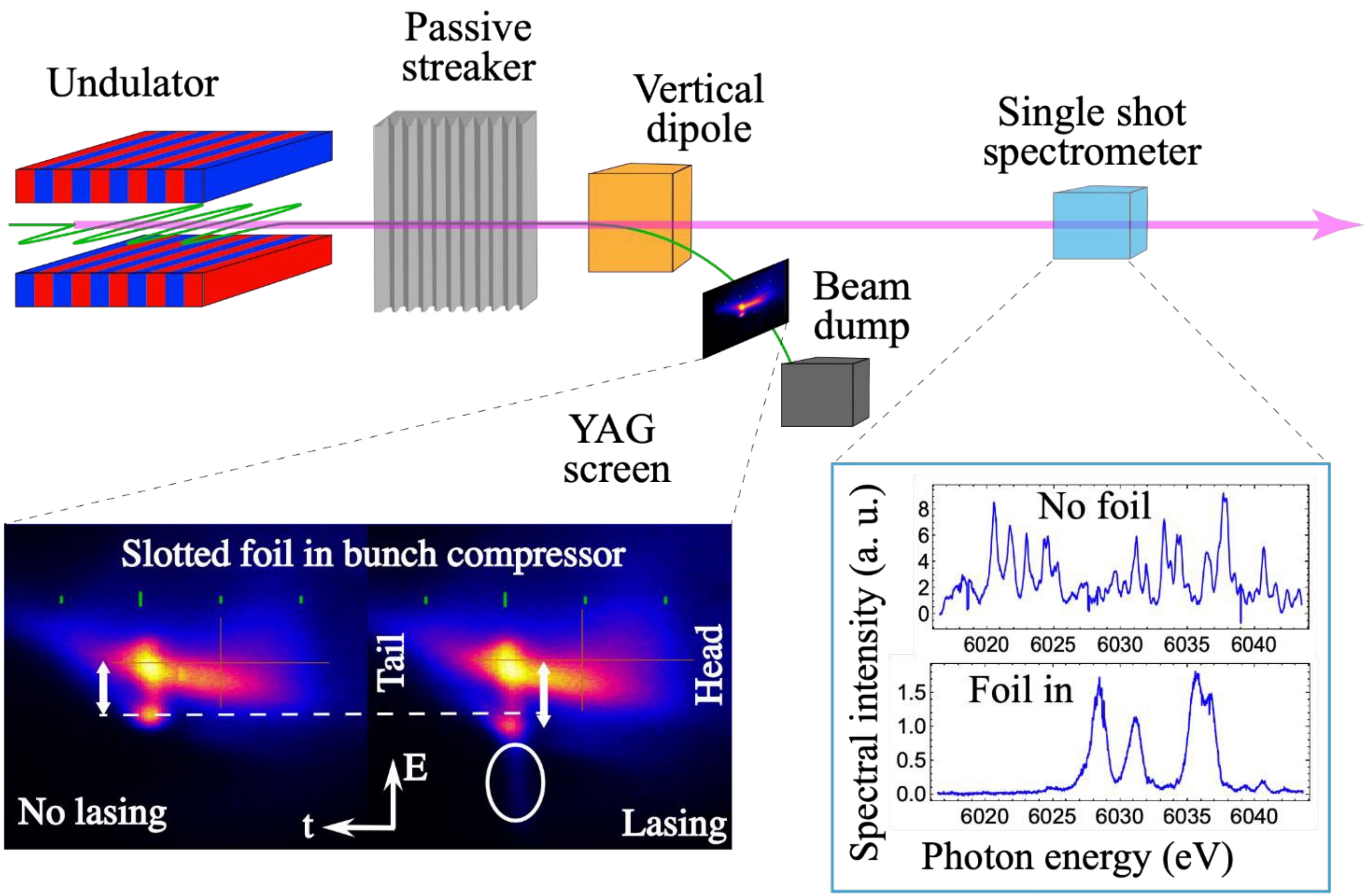
Photon beam:

- Direct streaking of the X-rays (very complicated approach)
- Spectral measurements with PSSS:
  - Spike number and width (works for short pulses)
  - Auto-correlation function (average pulse duration

Potential solution:

- Post-undulator time-resolved diagnostics
- An active deflector with high resolution is quite expensive
- Passive corrugated streaker can be an elegant and cheap solution

Post-undulator measurements with passive structure: first results for the lasing off/on:



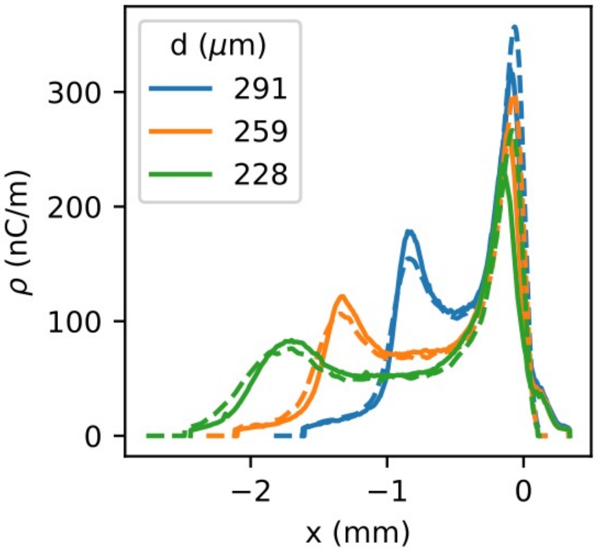
Right after installation of the device we have seen the first results, showing different longitudinal phase (nonlinear in time) for lasing off/on

Self-calibrated reconstruction approach

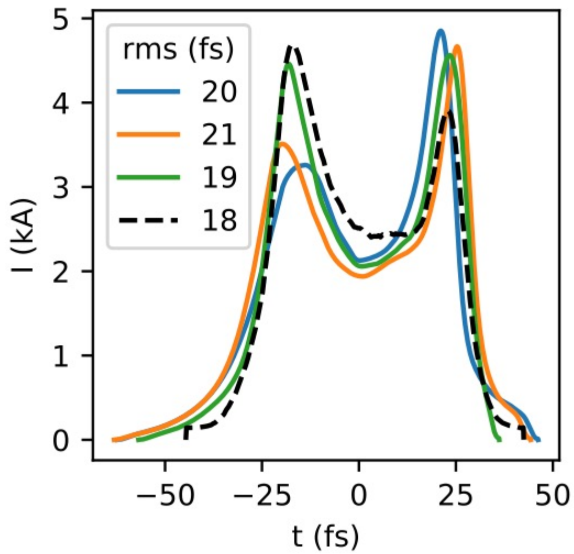
- It is essential to use passive streaker diagnostics if transverse deflector (or any other time-resolved diagnostics) is not available
- Self-calibration and reconstruction is possible utilizing an iterative procedure:
  1. Calculate mapping x(t) assuming an initial gaussian current profile of the certain size σ_t
  2. Obtain t(x) and transform the screen distribution $\rho_M(x)$ to obtain an intermediate reconstructed current profile $I_R^*(t)$
  3. Repeat steps 1 and 2 by calculating the x(t) profile for the x(t) estimation re-calculated for the intermediate current profile $I_R^*(t)$ to get $I_R(t)$
  4. Forward propagate $IR(t)$ to get the distribution $\rho_R(x)$ at the measurement screen
  5. Repeat 1-4 for different σ_t and find for which one the centroid of reconstructed $< \rho_R(x) >$ and measured $< \rho_M(x) >$ are in the best agreement for all streaker offsets

Self-calibrated reconstruction approach: results

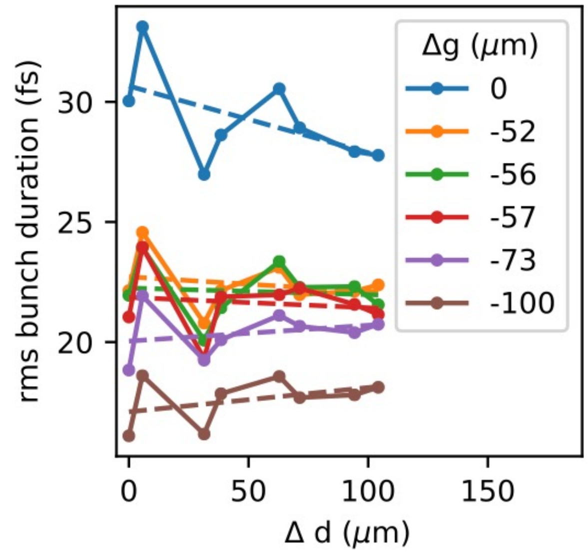
Measured (solid) and predicted profiles at the screen: $\rho_M(x)$ and $\rho_R(x)$



Measured with TDC (dashed) and reconstructed profiles:

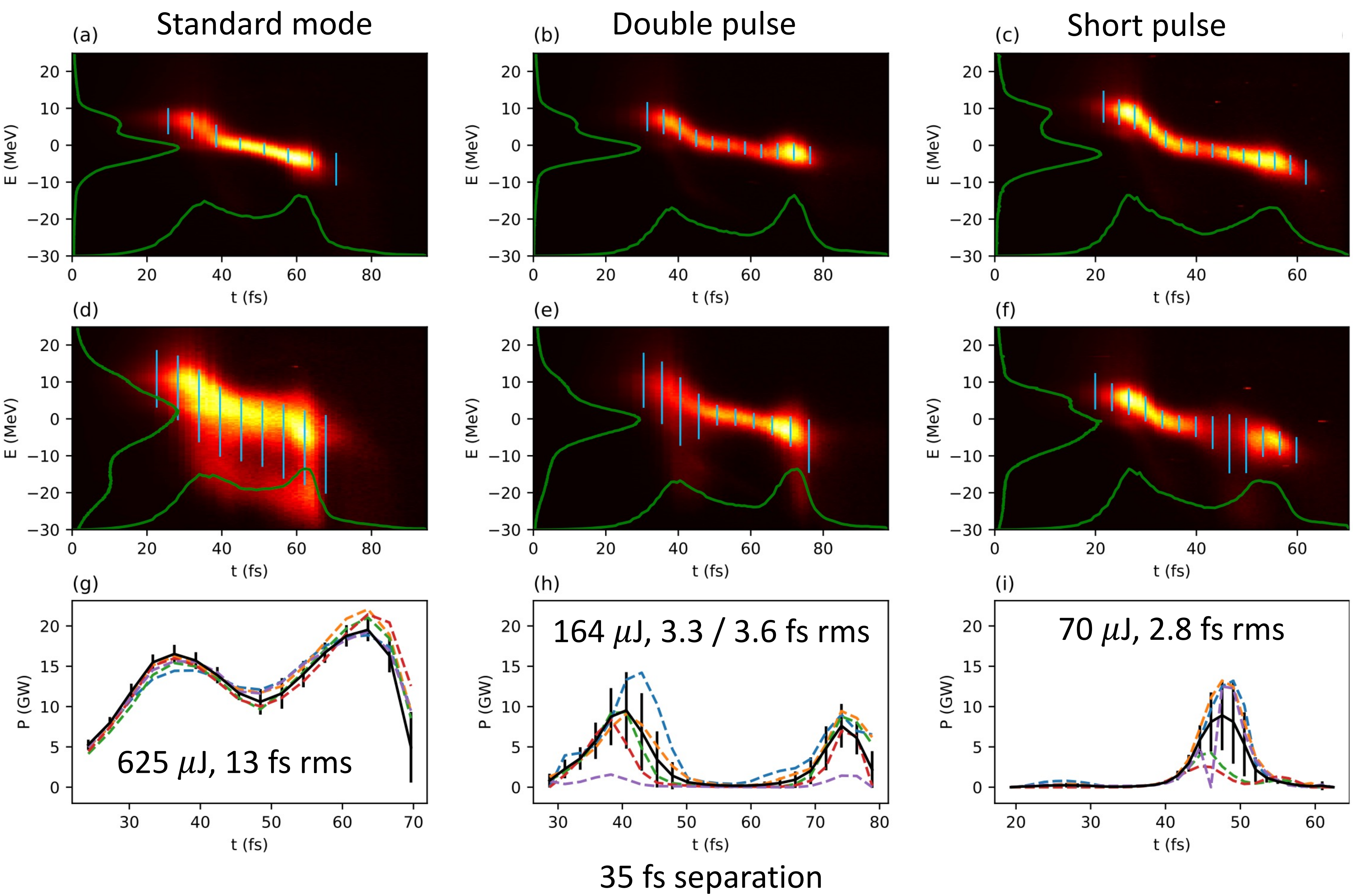


Gap reconstruction:



- The center of the structure is hard to define
- Distance of the beam to the corrugated plate, d, critically depends on it and strongly affects the reconstruction
- We add a correction factor Δg and find its optimum value assuming the reconstruction profiles should be similar for different offsets, d

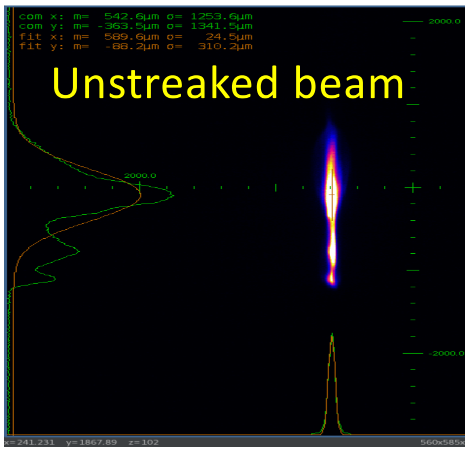
Diagnostics of variable lasing modes at SwissFEL



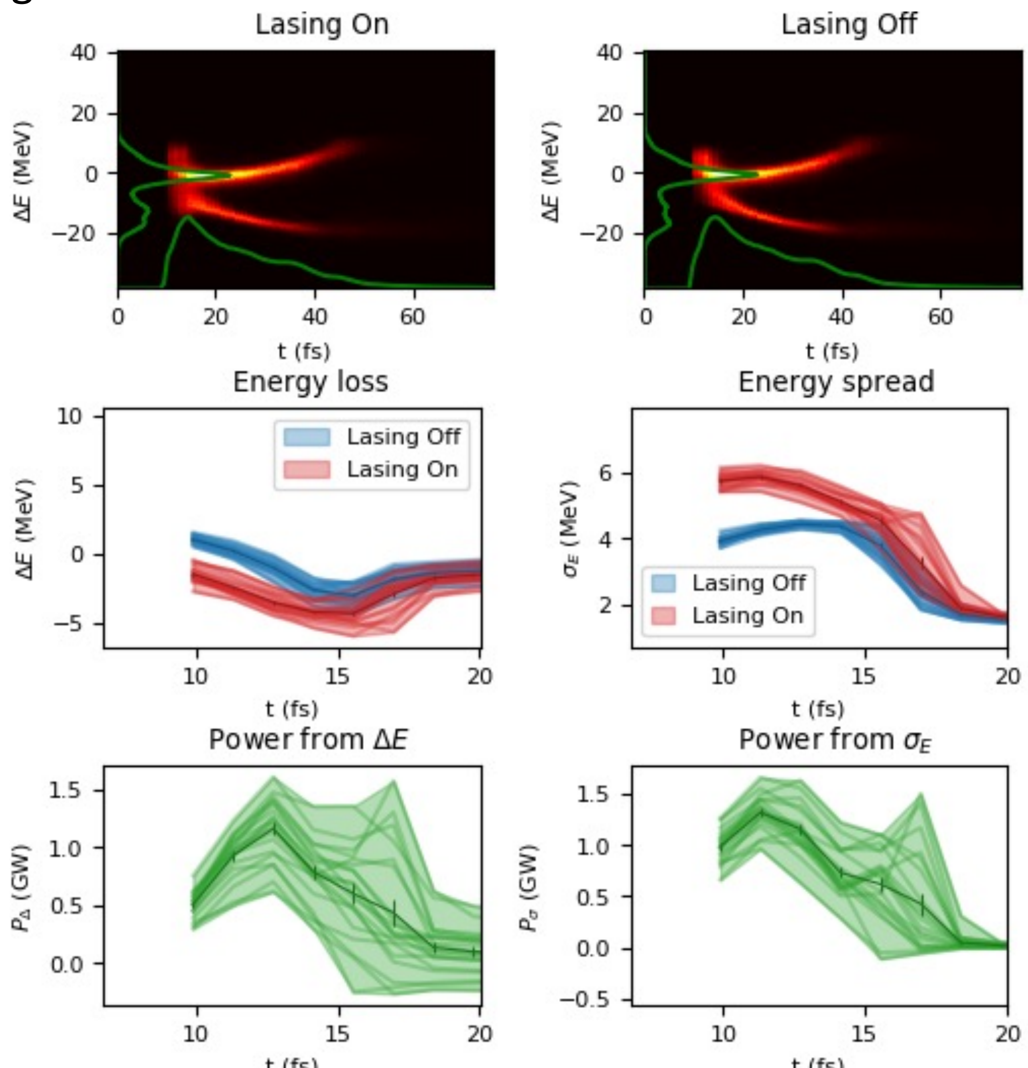
(more information: P. Dijkstal et al., *PRR 2, 042018(R), 2020*)

Recent results of the passive streaking: short 10 pC bunch

- ➢ The beam is prepared for generation of ultra-short pulses with non-linear compression (more information: Malyzhenkov et al., *PRR 2, 042018(R), 2020*)
- ➢ For this setup 10 pC bunch is strongly compressed and one expects to see a “K-shape” in the LPS due to Longitudinal Space Charge effects



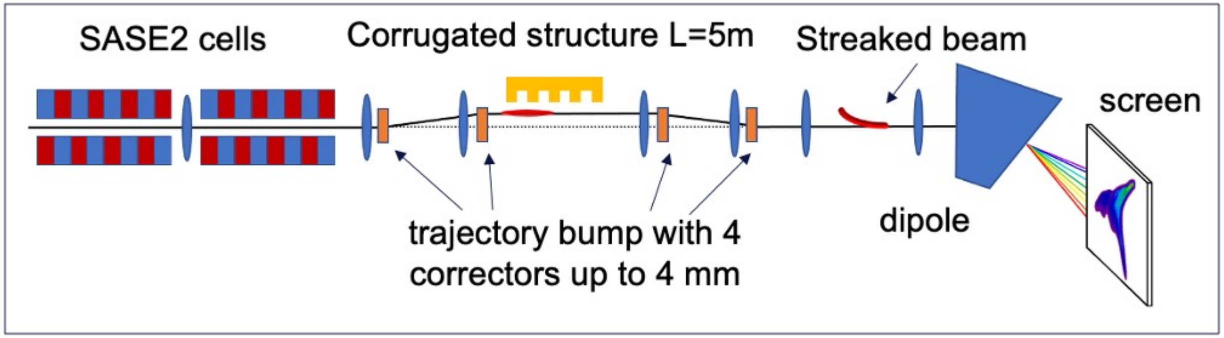
- ✓ Post-undulator passive structure can streak the 10-pC beam enough as well!
- ✓ Lasing effects are visible
- ✓ Reconstructed lasing part is longer than expected from spectral information (Insufficient resolution)



Brief look into the results at European X-ray Free Electron Laser (EXFEL) at DESY

Passive wakefield streaker (“dechirper”) diagnostics after SASE2

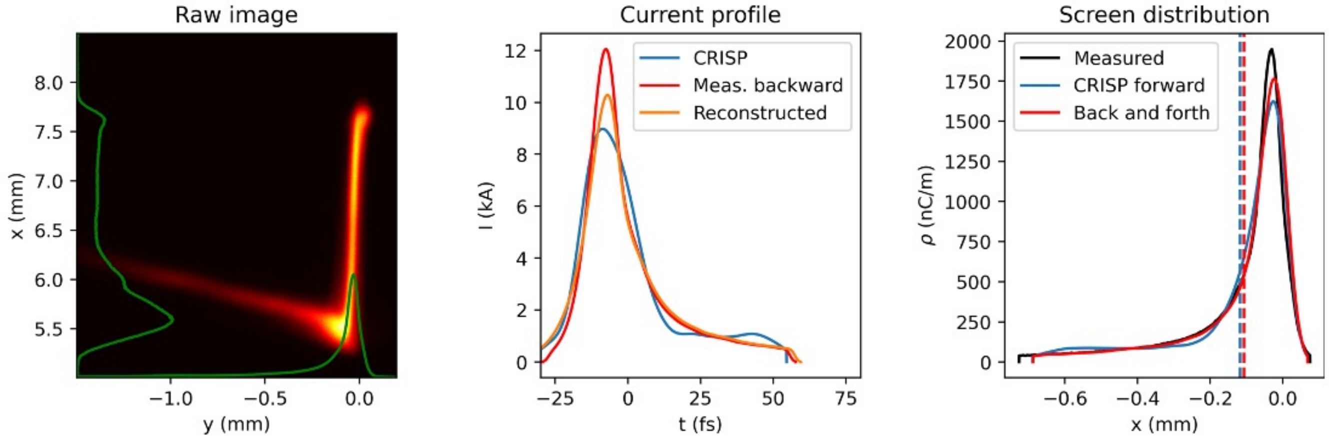
Layout: S. Tomin et al., IPAC 2022, MOPOPT020



Features:

- Corrugated plate is fixed
- Instead, beam is moved with correctors
- Dispersion (R_{26}) is negligible

Structure calibration based on CRISP online diagnostics



Calibration: vary structure plate position in calculations until c.o.m. of forward propagated CRISP current profile [N. Lockmann et al., Phys. Rev. Accel. Beams **23**, 112801 (2020)] matches that of the measurement (right plot). Orange current profile in center plot is the result of the current profile reconstruction following

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

European XFEL

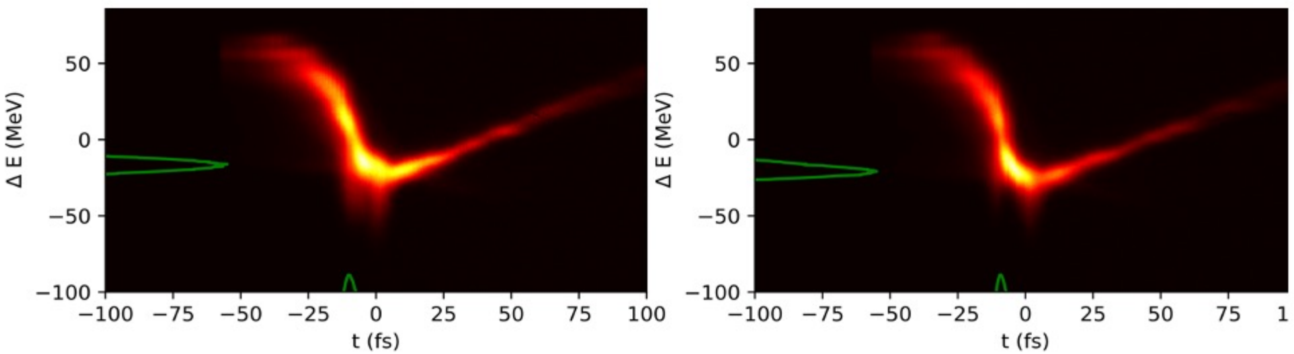
Courtesy of P. Dijkstal (adopted)

LPS diagnostics, following example of LCLS rf deflector:

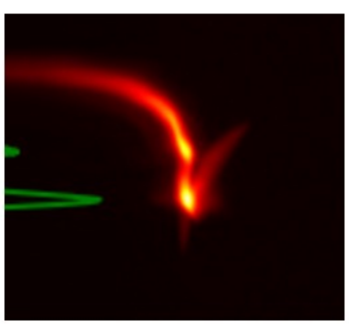
- convert streaked axis from y to t according to dipole wakefield potential: K. Bane et al, Phys. Rev. Accel. Beams **19**, 084401 (2016).
- linearly convert dispersive axis from x to energy.

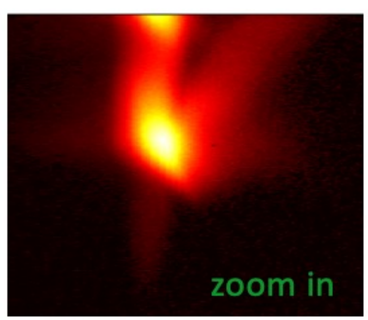
Example LPS measurements

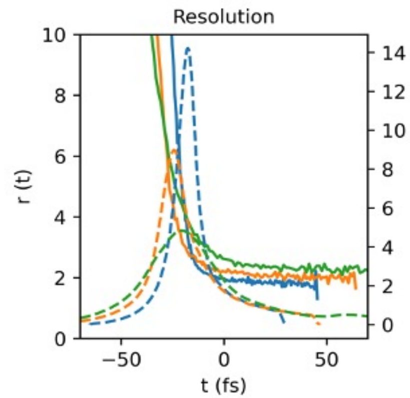
1. diagnosing problem with self-seeding setup. Here: sometimes two lasing regions, also seen in photon spectrum.



2. Short FEL pulses, here after strong compression at 250 pC. Rrms width of lasing region of few fs. Right: expected rms time resolution is also few fs for most of the bunch [P. Craievich and A. Lutman, NIM-A **865**, 55-59 (2017)].







European XFEL

Courtesy of
P. Dijkstal
(adopted)

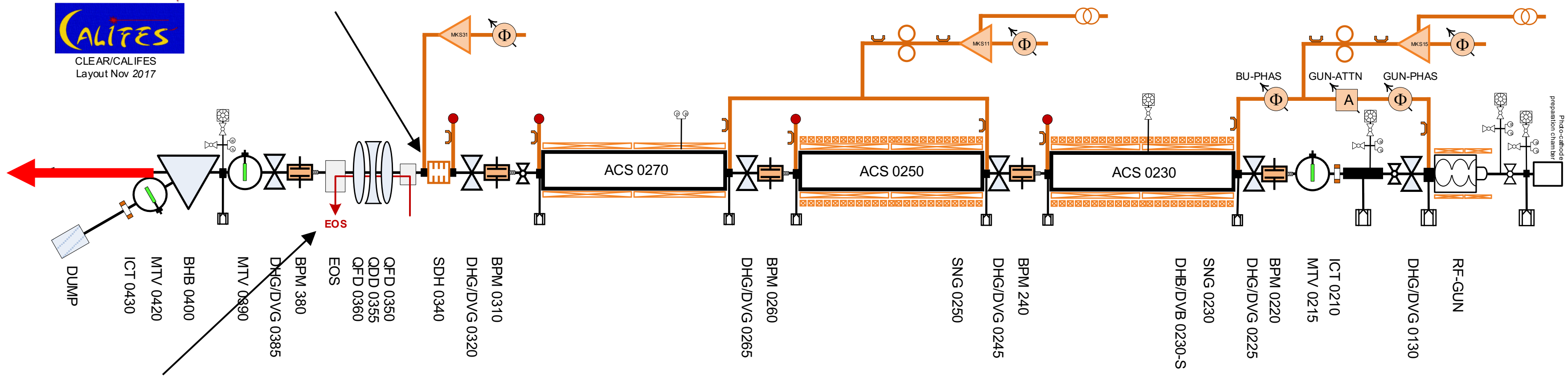
Development of the new device for CLEAR (CERN)

CLEAR = Compact Linear Electron Accelerator for Research

Development for the CLEAR accelerator at CERN

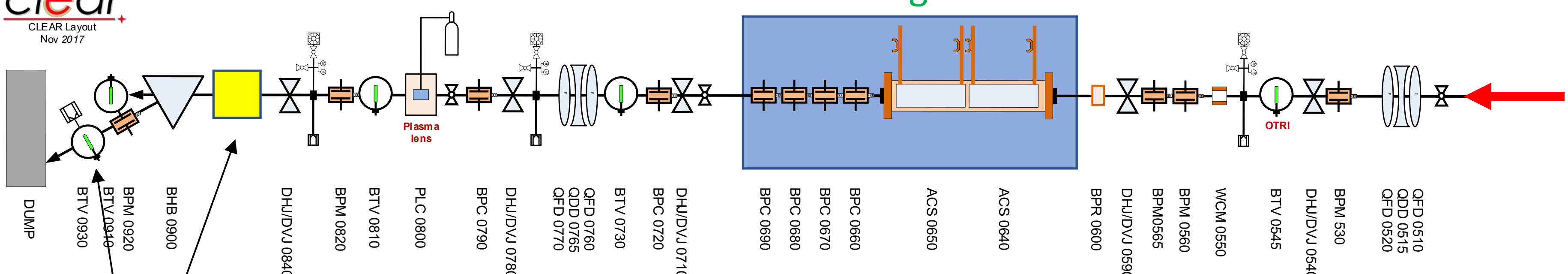
Layout (beam from right to left):

Transverse S-band deflector



Electro-optical sampling

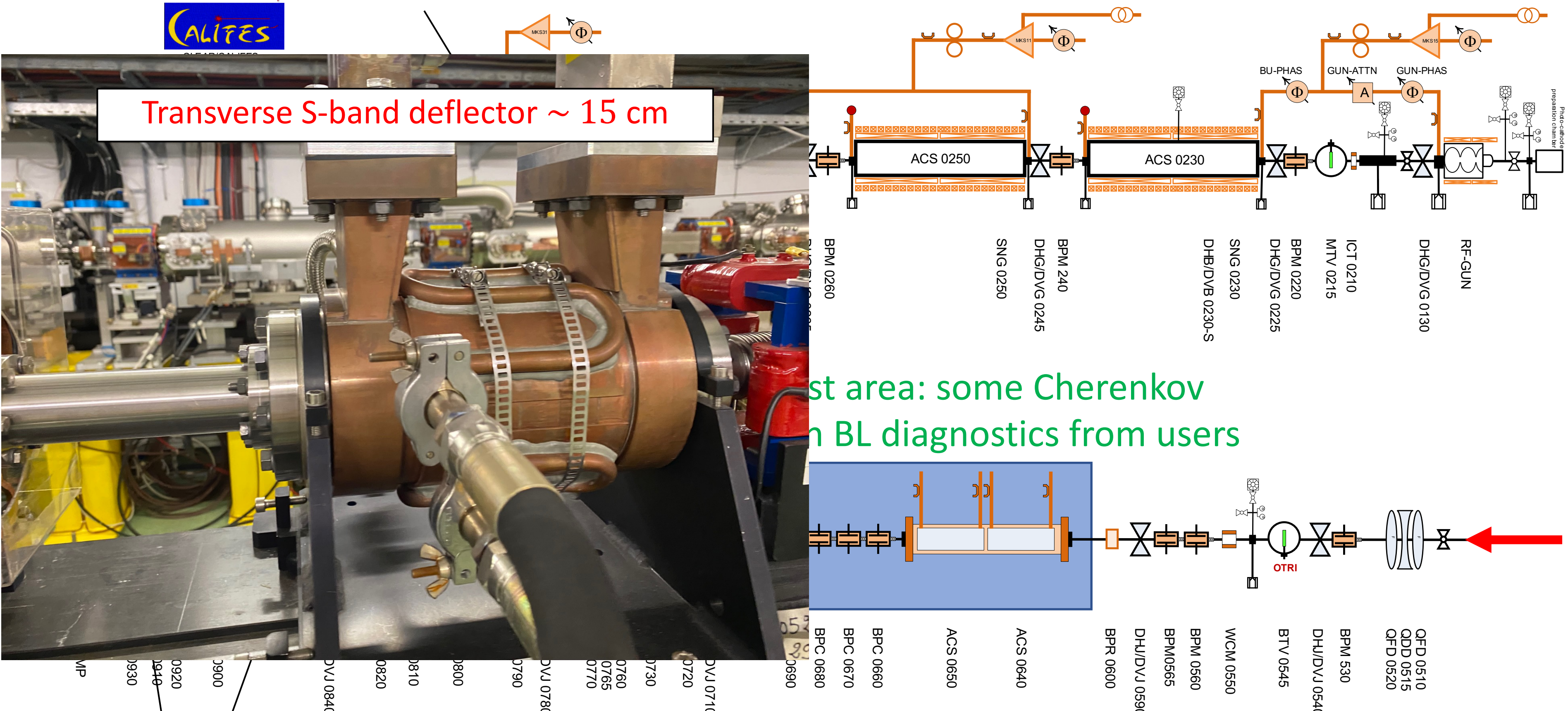
CLIC Test area: some Cherenkov diffraction BL diagnostics from users



- Transverse deflector in the first part of the machine is invasive for experiments downstream, and its resolution is limited to ~ 100 fs at 200 MeV
- Measurements at the end of the beamline can be essential for several users' experiments upstream: passive streaker can be an elegant and effective solution

Development for the CLEAR accelerator at CERN

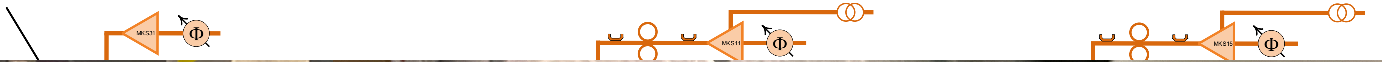
Layout (beam from right to left):

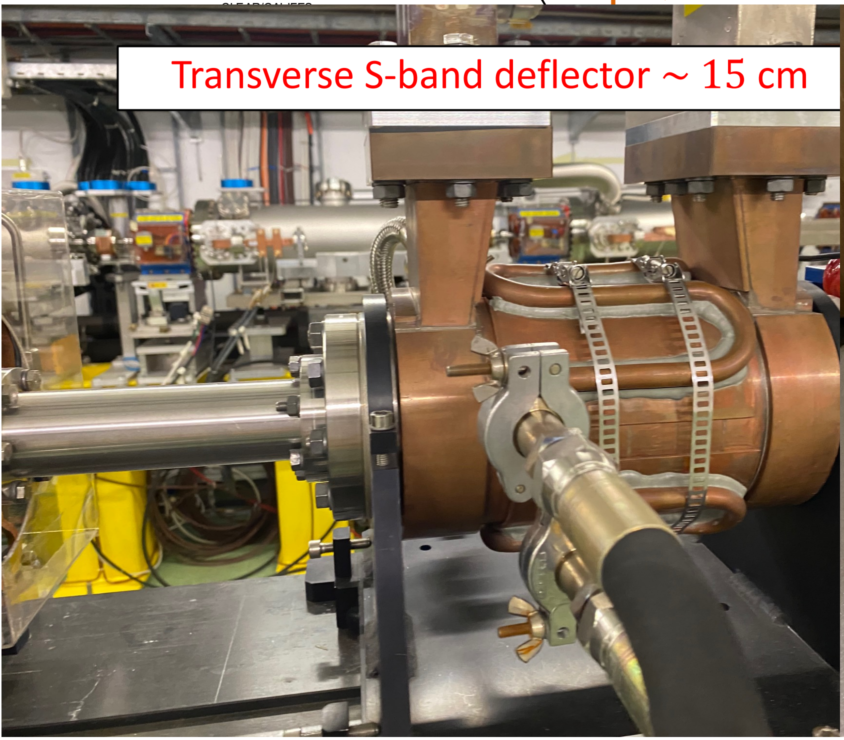


- Transverse deflector in the first part of the machine is invasive for experiments downstream, and its resolution is limited to ~ 100 fs at 200 MeV
- Measurements at the end of the beamline can be essential for several users' experiments upstream: passive streaker can be an elegant and effective solution

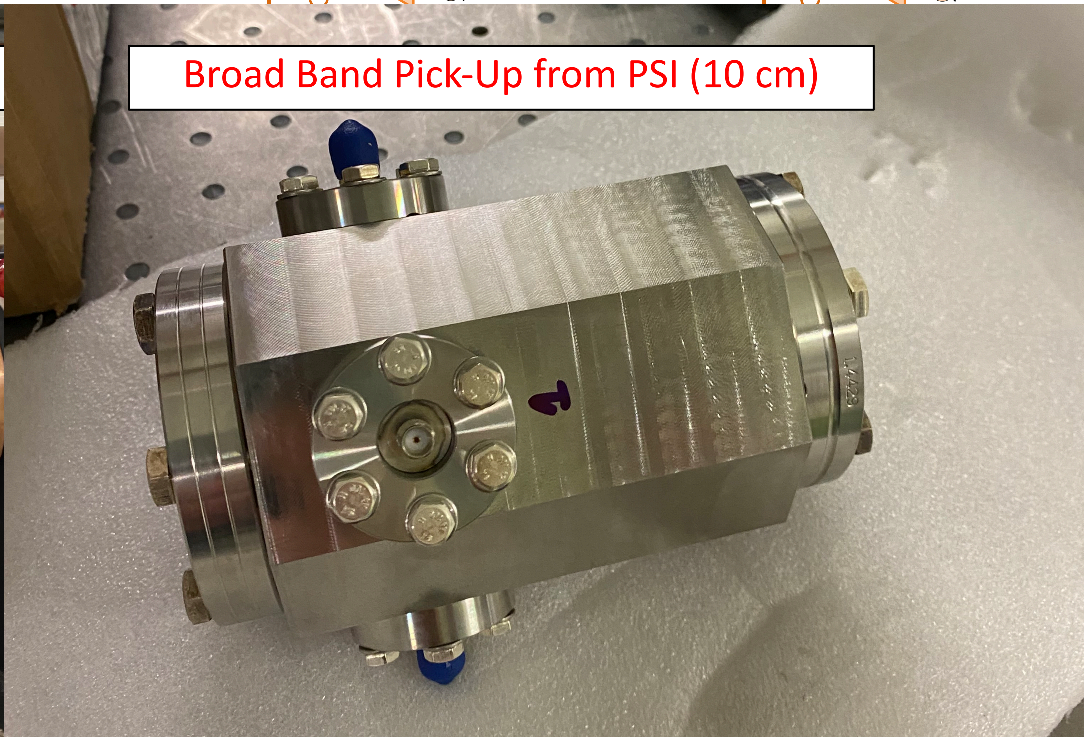
Development for the CLEAR accelerator at CERN

Layout (beam from right to left):





Transverse S-band deflector ~ 15 cm

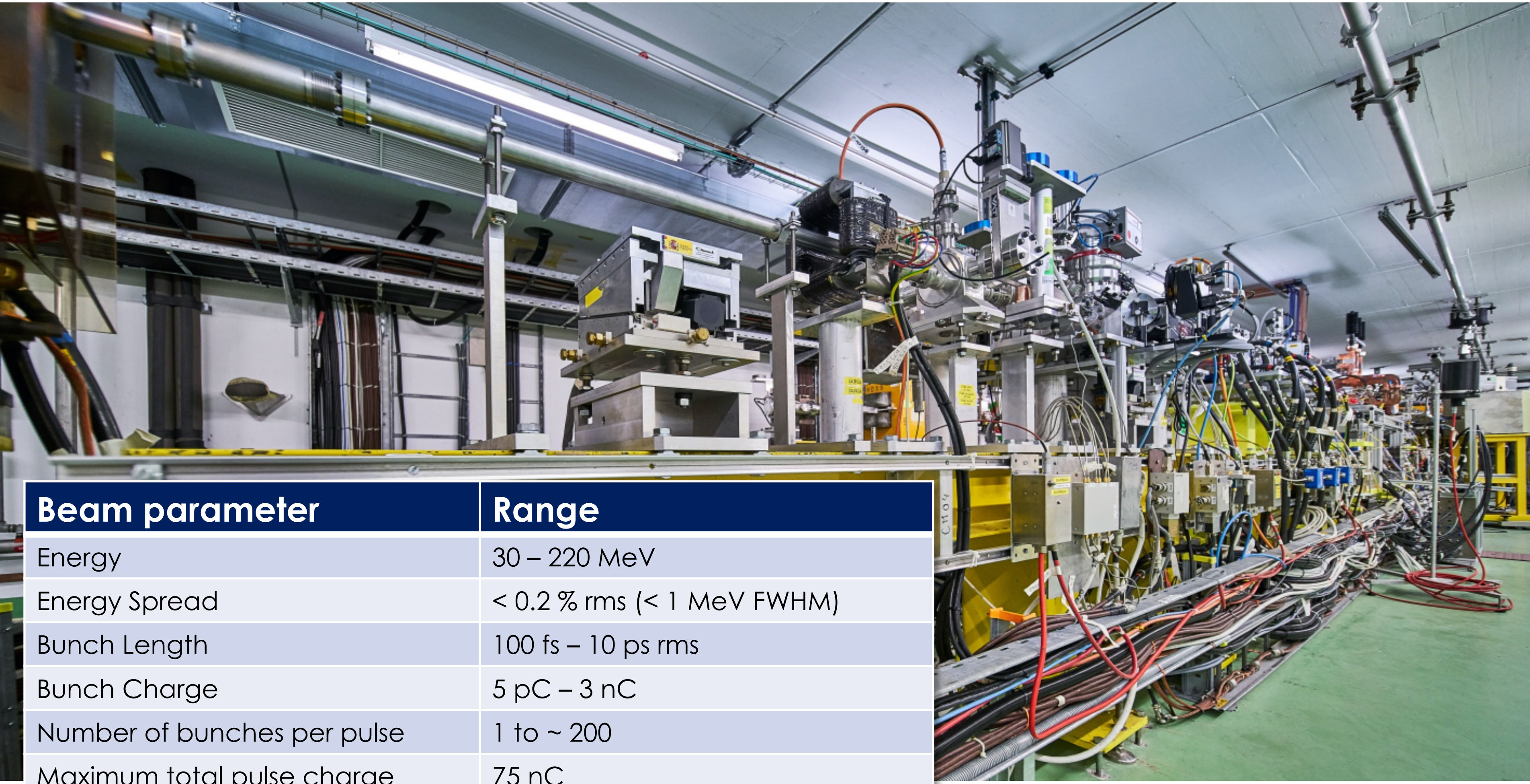


Broad Band Pick-Up from PSI (10 cm)

BBP (new development for electron-positron source temporal diagnostics):

- To be tested in November 2023 at CLEAR by PSI Team
- Current profile reconstruction should be feasible
- For more details contact Nicolas Valis (nicolas.vallis@psi.ch) and Paolo Craievich (paolo.craievich@psi.ch)

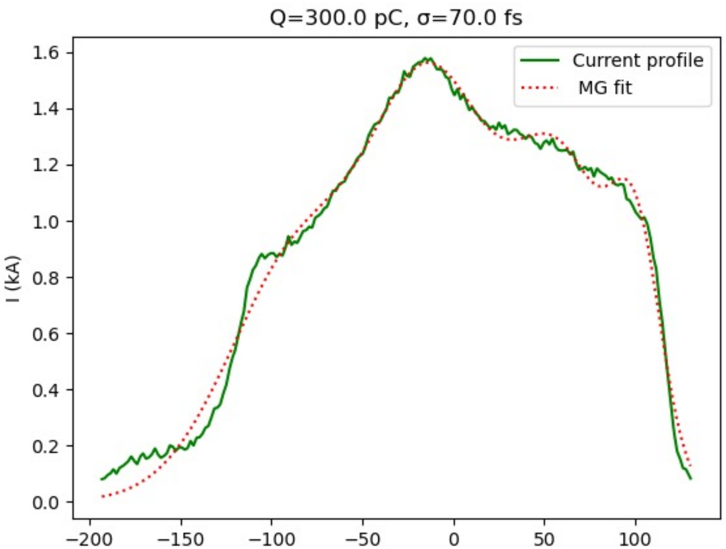
CLEAR beam parameters



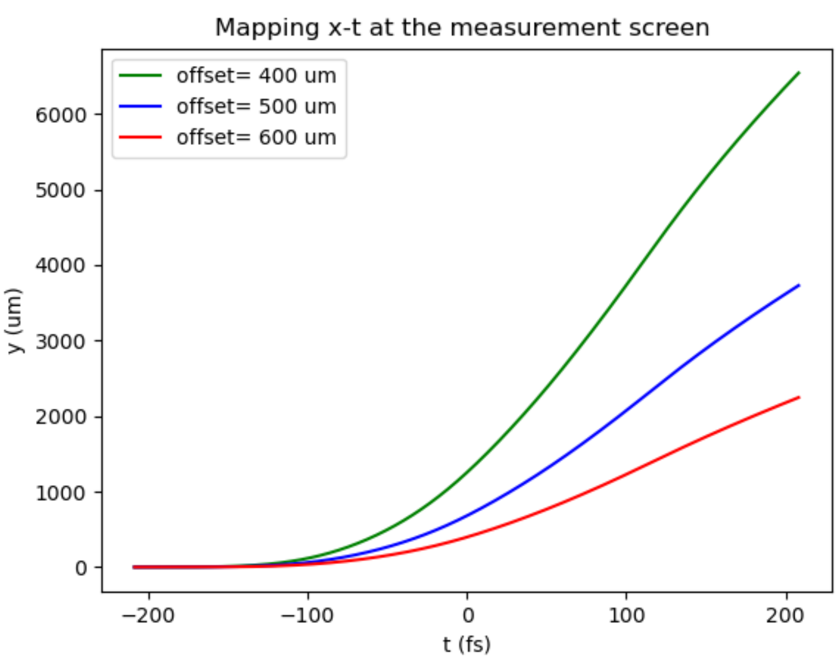
Beam parameter	Range
Energy	30 – 220 MeV
Energy Spread	< 0.2 % rms (< 1 MeV FWHM)
Bunch Length	100 fs – 10 ps rms
Bunch Charge	5 pC – 3 nC
Number of bunches per pulse	1 to ~ 200
Maximum total pulse charge	75 nC
Normalized emittances	3 μm to 30 μm (bunch charge dependent)
Repetition rate	0.8 to 10 Hz
Bunch spacing	1.5 GHz (from Laser) – 3.0 GHz (Double mode)

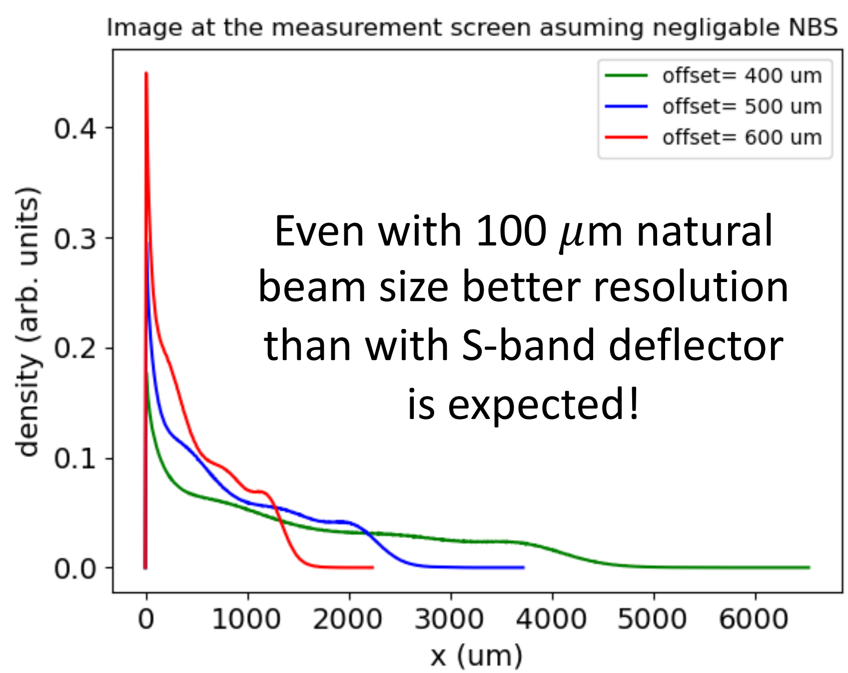
Optimization of the corrugated streaker parameters is essential to maximize the performance in the whole range of parameters

Wakefield calculations and streaking for short pulses



- Assuming 20 cm length of the streaker
- 500 / 1000 μm corrugated depth / period
- Corrugated plates will be machined at CERN workshop (practically for free thanks to the apprenticeship program)

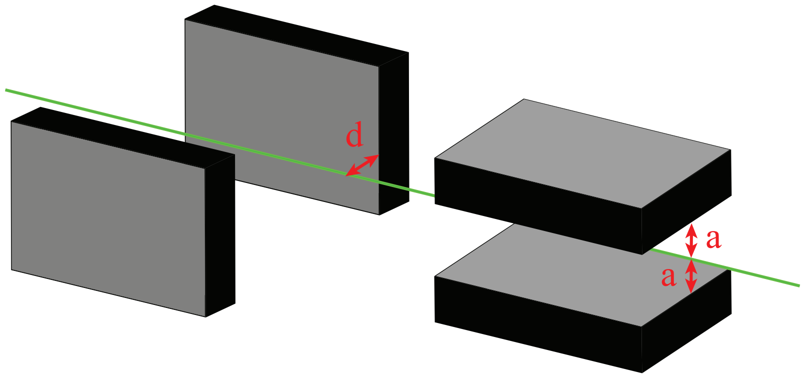




New things which can be tried experimentally at CLEAR

Quadrupole effect compensation with two orthogonal structures:

- First structure (off-axis) streaks the beam horizontally
- Second orthogonal structure (on-axis) compensates quadrupole effect from the previous structure when semi-gap a is optimized for each d



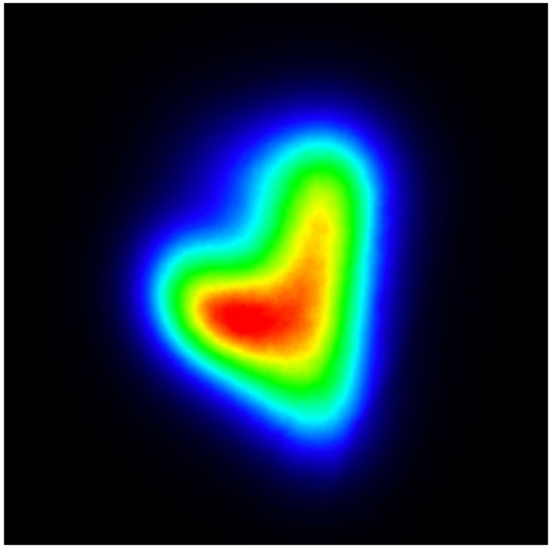
Two consequent electron bunches from two laser pulses:

- 1st bunch initiates transverse wake while moving off-axis
- 2nd bunch experience a large transverse kick and get streaked
- Since we can control charge in both bunches independently and time separation the resolving power of such streaking can be very large

Conclusion & next steps

- ✓ Time-resolved diagnostic with passive streaking has been advanced and works great!
- ✓ It is also an order of magnitude cheaper than active deflector and does not require a power supply
- ✓ It is now routinely used at SwissFEL at PSI (and at EXFEL)
- ✓ The method still has a potential to be improved: resolution optimization, elimination of quad effects with two structures
- ✓ The corrugated passive streaker optimized for CLEAR beam parameters is under-development and soon to be fabricated, assembled, and tested (stay tuned!)

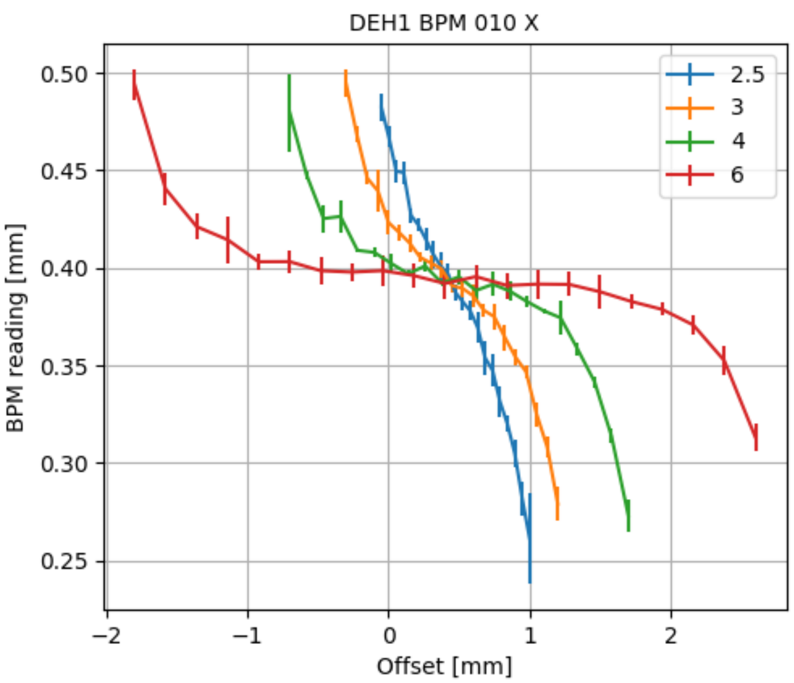
Thank you for your attention!

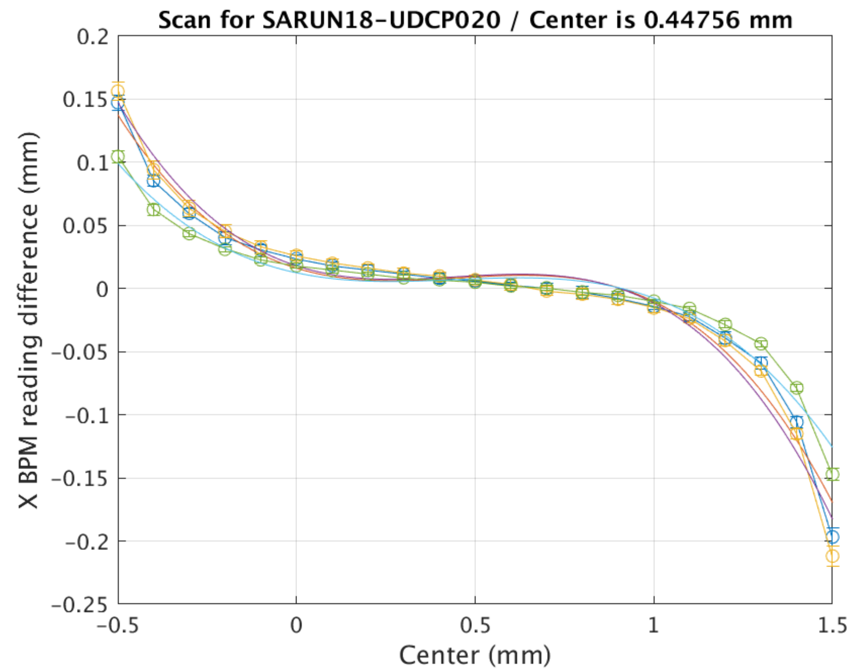


Back up slides

Defining the geometric center of the structure:

Measuring the centroid kick for different offsets at different BPMs:
Geometric center = no kick (no transverse wakefields excited)





Geometric center is roughly at 500 μm off axis
It is easy to make a mistake of 10-30 μm: uncertainty of the actual distance to the jaw!
Need proper fit for the reconstruction

Resolution: formulas

"Effects of the quadrupole wakefields in a passive streaker", P. Craievich and A.A. Lutman, NIM A **865**, 55 (2017):

Resolution:

$$\sigma_{res}(t) = \frac{\sqrt{\sigma_{scr}^2 + \sigma_{NBS}^2 + \sigma_q(t)^2}}{dx/dt}$$

- σ_{scr}- screen resolution, can be mitigated by choosing larger R_{12}
- $\sigma_{NBS} = \sqrt{\epsilon_x(\frac{{R_{12}}^2}{\beta} + (R_{12}\alpha - R_{11}\beta)^2)} \rightarrow \min(\sigma_{NBS}) = \frac{\epsilon_x R_{12}}{\sigma_0}$, if $R_{12}\alpha = -R_{11}\beta$
- R – linear transport matrix from the passive structure to the measurement screen, β, α and σ_0– horizontal twiss parameters and bunch size at the passive structure
- Quadrupole effects: $\sigma_q(t) = \sqrt{\epsilon_x(K_1(t)^2 {R_{12}}^2 \beta - 2K_1(t)R_{12}(R_{12}\alpha - R_{11}\beta))}$
- For minimum of σ_{NBS} we have: $\sigma_q(t) = K_1(t)R_{12}\sigma_0$
- $\frac{dx}{dt} = R_{12}\,\frac{dK_0(t)}{dt}$
- $K_0(t)$ and $K_1(t)$ - dipole and quadrupole kicks of the passive

Resolution: optimization σ_0 and d

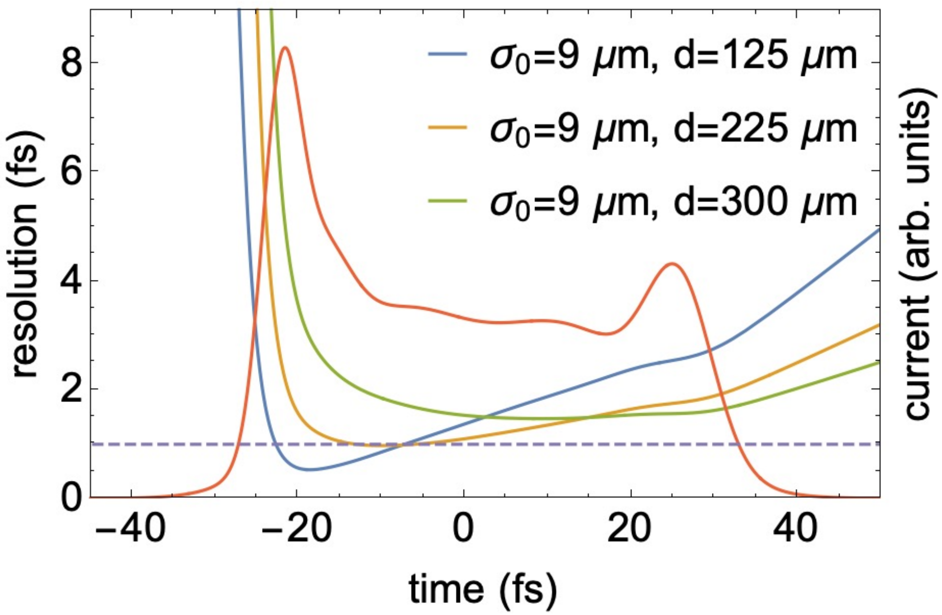
Resolution depends on:

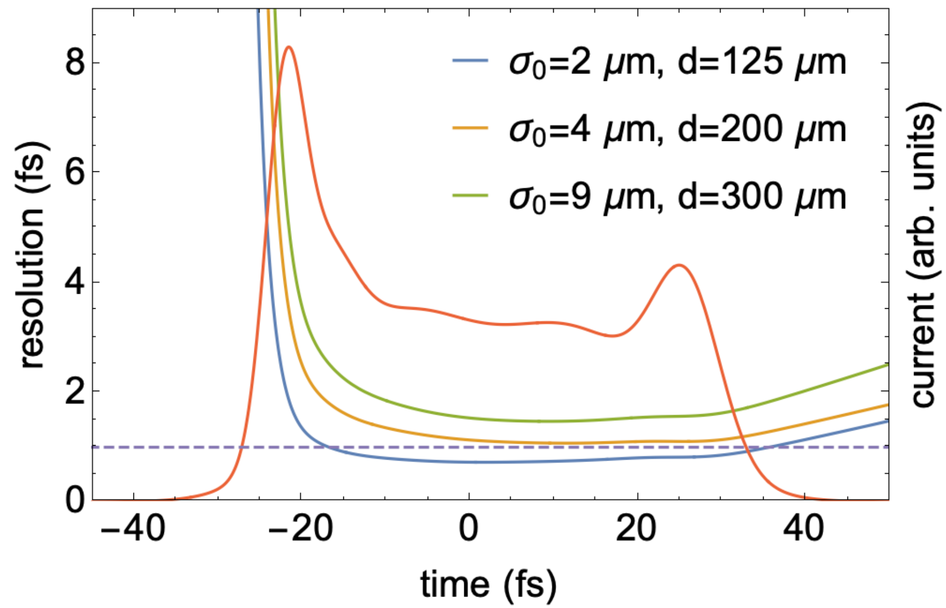
- Distance to the jaw, d
- Bunch size at the passive streaker, σ_0
- Bunch size at the screen, σ_{NBS}
- Optics optimization*: $R_{12}\alpha = -R_{11}\beta$,

β, α horizontal twiss parameters at the passive structure, R – transport matrix

$$\sigma_{res}(t) = \frac{\sqrt{\sigma_{scr}^2 + \sigma_{NBS}^2 + \sigma_q(t)^2}}{dx/dt}$$

*minimum size at the screen for fixed size at the streaker





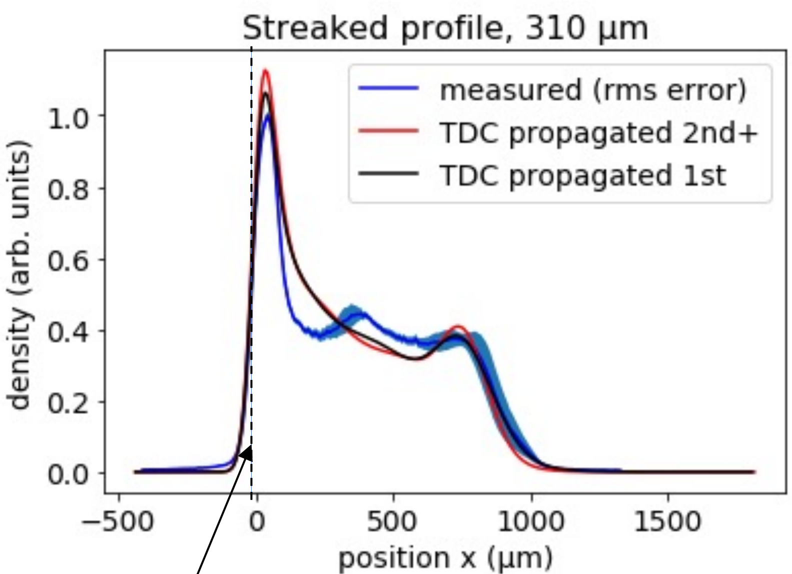
Getting closer to the jaw and picking the smallest possible size at the streaker location = better resolution!

Reconstruction of the current profile with TDC calibration

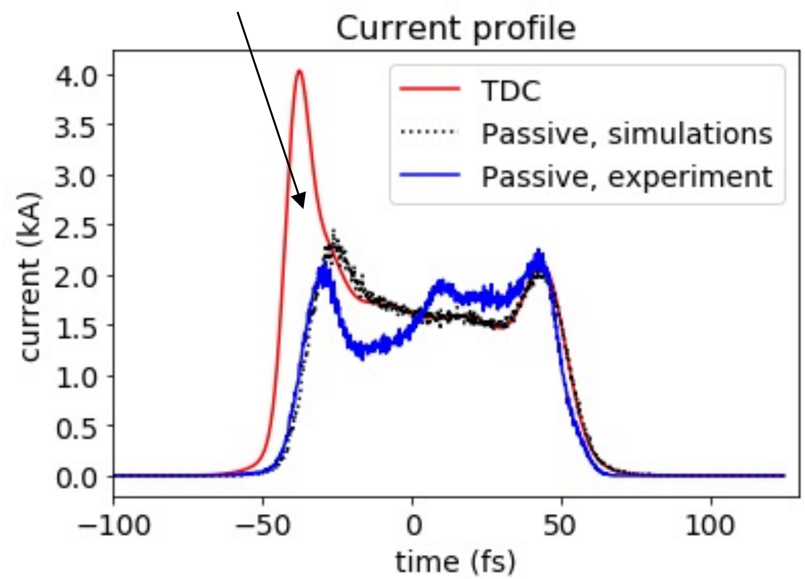
- Benchmark the theoretical model (Bane et al., PRAB 19, 084401, 2016) at the measurement screen location

- Use it to back-propagate the measured distribution to the time domain, using TDC-based calibration

Poor resolution in the head of the bunch, because particles for x<0 are lost



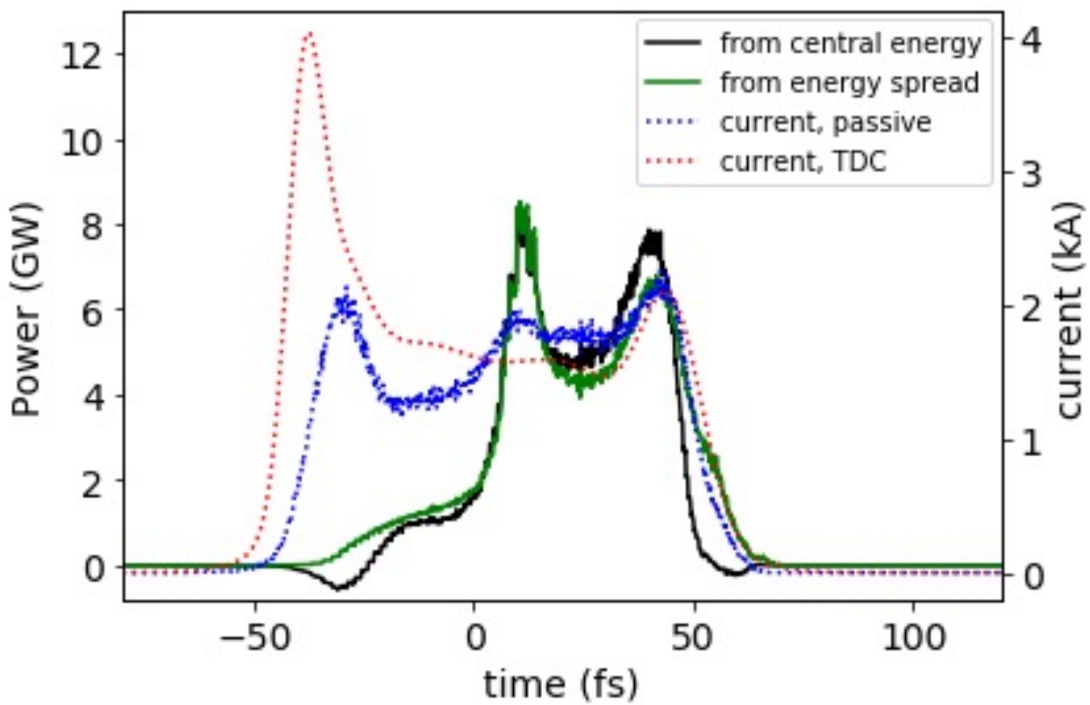
Defined by the centroid of the unstreaked beam



Good agreement between measurements and simulations!

First reconstruction of the power profile

After doing a proper slice analysis along the bunch, we reconstruct the lasing power profile with two method:



Pulse energy:

- **280 μJ** from gas detector
- **287 μJ** from central energy (absolute)
- **310 μJ** from energy spread (peak power matched)

Pulse duration

- Electron beam: **40 fs** rms
- Photon beam: **18 fs** rms