Eduard Prat :: SwissFEL Beam Dynamics :: Paul Scherrer Institut

Requirements on electron beam instrumentation for beam dynamics and operation of a free-electron laser

WP13 EuPRAXIA electron and photon diagnostics

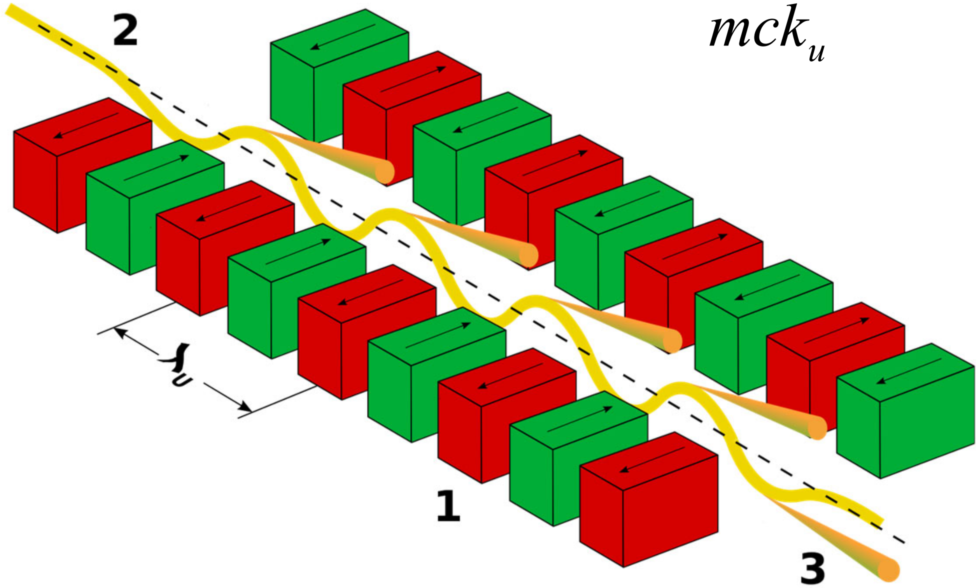
EPFL, Lausanne, 12 June 2023

Contents

- Electron beam requirements for X-ray FELs
- Electron beam instrumentation requirements
- Emittance and time-resolved measurements
- Some important resolutions, implication to optics and transverse profile monitor (PM) resolution
- FEL properties from electron beam properties
- Summary and conclusion

Contents

Electron beam energy



$$K = \frac{eB_0}{mck_u}$$

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

The electron beam energy needs to be at the GeV level for X-rays

Peak current and beam sizes

Pierce parameter

$$\rho = \frac{1}{\gamma_0}\left[\left(\frac{f_c K}{4k_u\sigma_x}\right)^2 \frac{I}{2I_A}\right]^{\frac{1}{3}}$$

Gain length

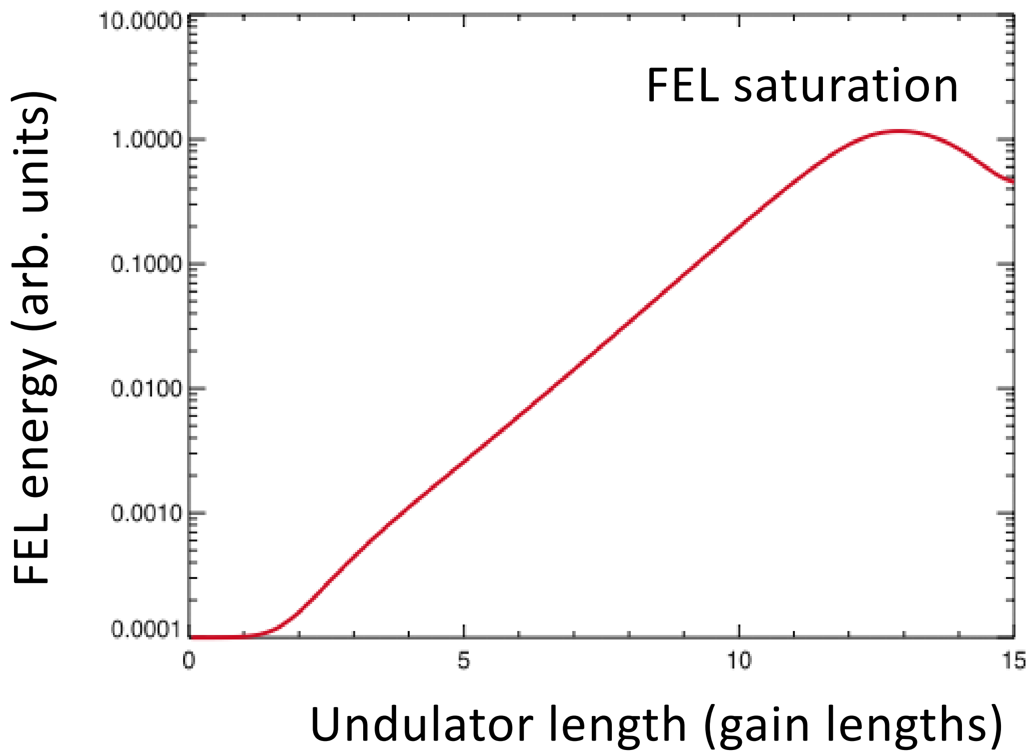
$$L_g = \frac{\lambda_u}{4\pi\sqrt{3}\cdot\rho}$$

Efficiency

$$P_{FEL} \approx \rho P_{beam}$$

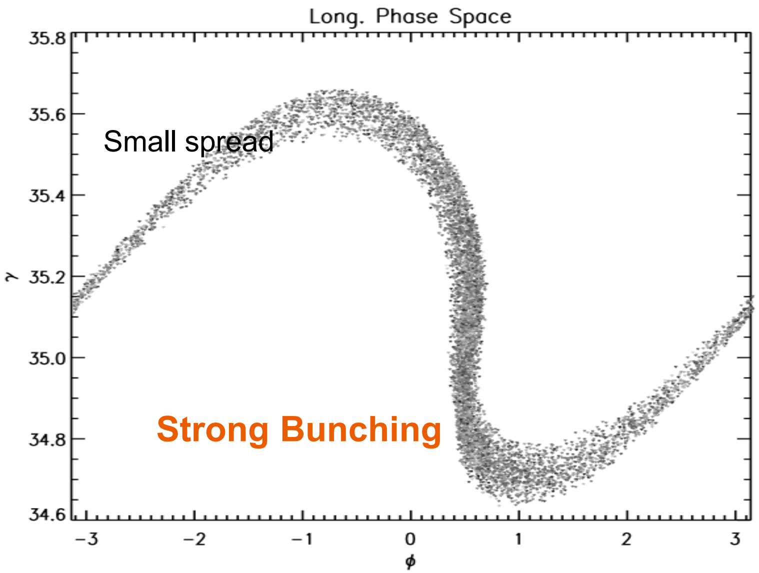
A better FEL performance, i.e. higher powers and shorter gain lengths, are obtained for larger ρ parameters. We want:

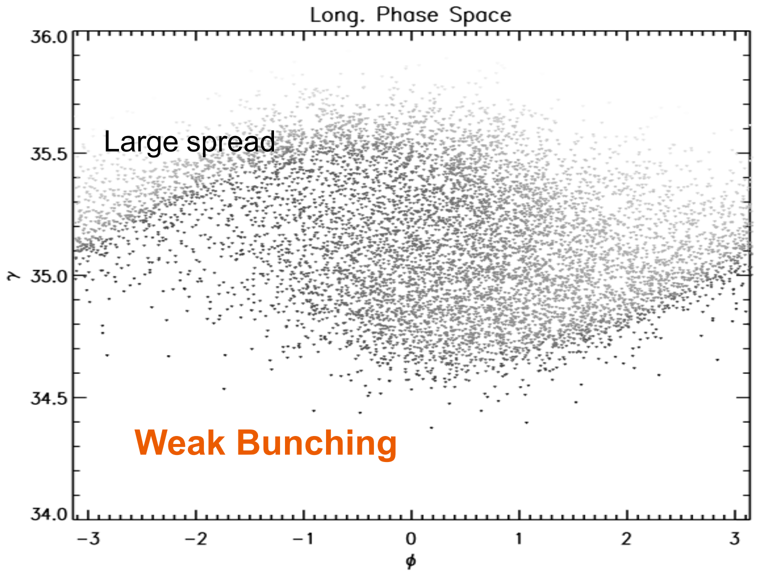
- Large peak currents (from 1 to several kA)
- Small transverse beam sizes (10s of μm)
- (Larger undulator fields *K*, but require higher electron beam energies for the same wavelength)



Energy spread

- Only electrons within the FEL bandwidth can contribute to FEL gain.
- The FEL bandwidth is approximately equal to the ρ parameter
- Consequently, the relative energy spread needs to be smaller than ρ





Energy spread constraint:

$$\frac{\sigma_E}{E} < \rho$$

For X-rays: relative energy spread needs to be smaller than $10^{-3} - 10^{-4}$

- Besides this limit: lower energy spreads are desired → better FEL performance and shorter pulses
- Standard FEL injectors have relative energy spreads of ~1e-5 (energy spread resolution should be better than that)

Emittance

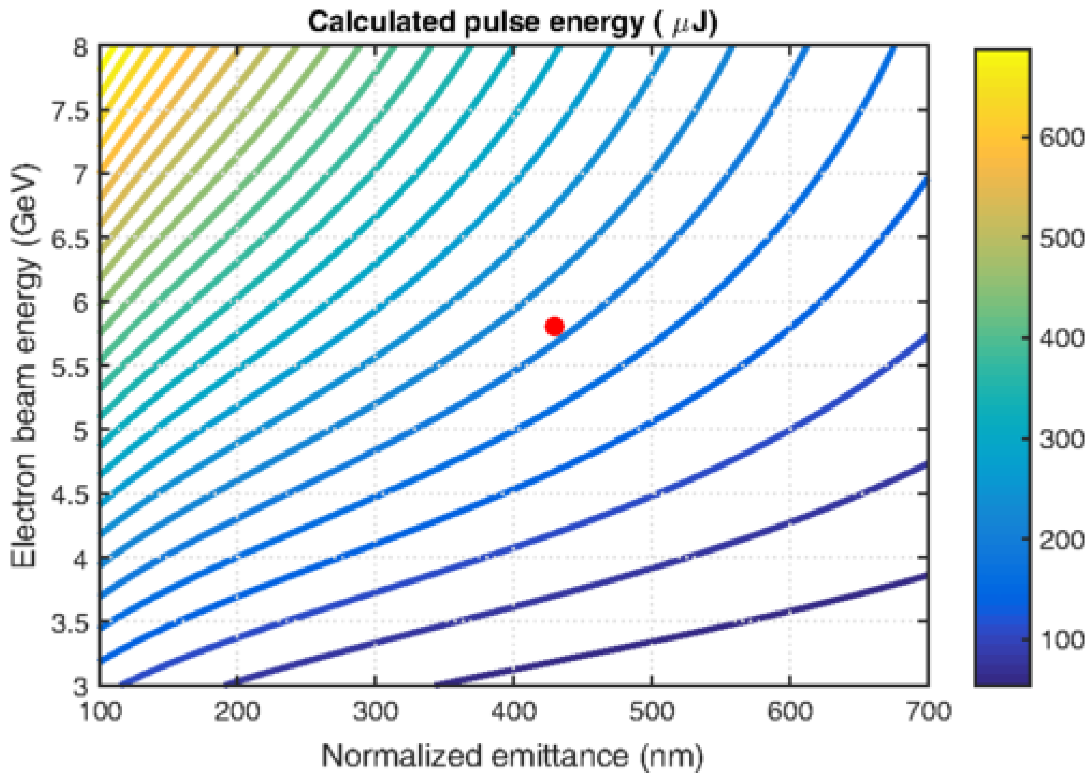
- Transversely coherent FEL radiation is generated when

$$\frac{\varepsilon_n}{\gamma} \approx \frac{\lambda}{4\pi}$$

- If the normalized emittance is reduced:
  1. **The final beam energy can be decreased →more compact and cheaper accelerator**
  2. **Higher radiation power and shorter undulator line for a given beam energy**

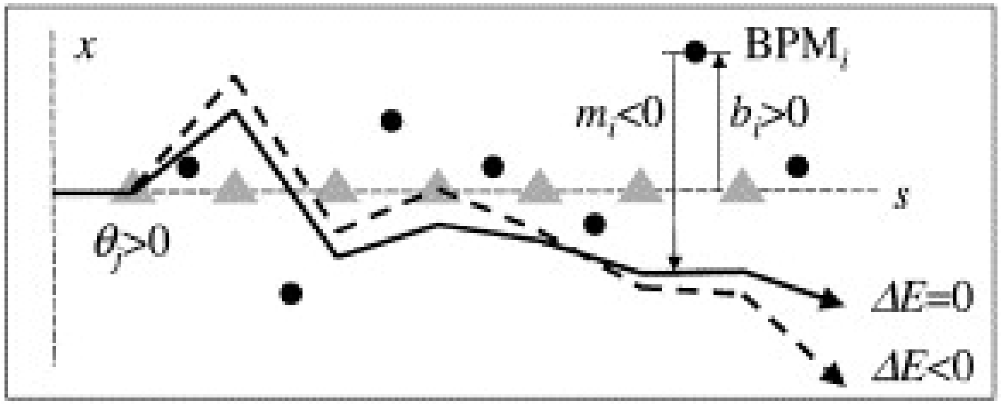
- FEL injectors produce normalized emittances down to several tens of nanometers – resolutions of ~10 nm required

Calculations for SwissFEL at 0.1 nm



Transverse overlap

- FEL performance strongly depends on a good transverse overlap between electrons and photons. Therefore we need to control:
  - Trajectory: with beam-based alignment (sub µm control required)
  - Beam size: with optics matching



Time-resolved properties

- FEL process occurs within a small fraction of the bunch length and properties can vary along the longitudinal beam position → need for time-resolved measurements and optimization
  - Slice current
  - Slice emittance
  - Slice optics
  - Slice trajectory

- FEL pulse duration is mostly defined by the electron beam pulse duration which is able to lase (proper current, emittance, trajectory, etc.). The lower limit is the FEL slippage (100's of as for X-rays).

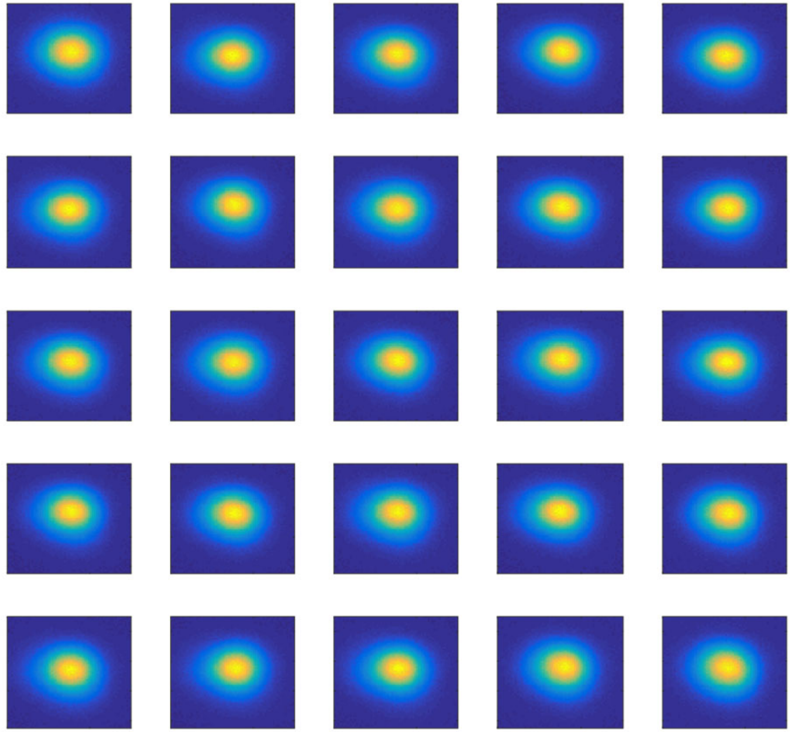
- Standard pulse duration is of few tens of fs. Short pulses below 1 fs have been achieved in X-rays in different ways

→ need to measure time-resolved properties with at least few fs resolution, ideally with sub-fs resolution

High and stable FEL performance

- Scientific users require extremely stable FEL radiation output in terms of:
  – pulse energy (~% level)
  – arrival time (~10 fs)
  – wavelength (~0.1%)
  – pointing (~10% of beam size).

- Several feedbacks are used for that:
  – Charge feedback (gun laser)
  – Trajectory feedbacks along the machine
  – Compression (current) feedbacks after each bunch compressor
  – Arrival time feedbacks
  – Electron beam energy feedbacks



Example: shot to shot FEL spots at SwissFEL. Intensity stability of few %, pointing stability around 10% of the rms beam size

Contents

PAUL SCHERRER INSTITUT PSI

Properties to be measured

- In FEL facilities, electron beam diagnostics are required to characterize, optimize, and stabilize the electron beam for best FEL performance

- We need to diagnose:
  - How many electrons we have: charge
  - First-order moments: transverse trajectory, energy and arrival time
  - Second-order moments: transverse beam sizes and divergences, energy spread, pulse duration, optics and emittances
  - The above as a function of time: current, transverse tilts, energy chirp, slice optics and emittance, slice energy spread
  - Moreover: radiation loss monitors to protect people and machine (not consider after in this talk)

Other aspects

Repetition rate and invasiveness

- Here we limit ourselves to ~100 Hz facilities (as EuPRAXIA will be)
- Some properties need to be stabilized in feedbacks and therefore must be measured in full rep rate and non-invasively; e.g. trajectories, compression signals, etc.
- Some other properties do not require to be measured in full rep rate and can be measured invasively; e.g. the emittance (but would be nice to!)

Absolute and relative measurements

- Some devices give absolute measurements, some others only relative but can be calibrated.
- Example: rf streaking measurements (absolute, invasive) and compression monitors (relative, non-invasive).

Overview of required diagnostics

	Range	FB	State-of-the-art devices
Charge	~1 pC - ~1 nC	Yes	ICT or BPM (rel.)
Trajectory	<1 µm to few mm	Yes	BPMs
Energy	~1 MeV to ~10 GeV	Yes	Dipole + BPM
Arrival time	~1 fs to ~10 ps	Yes	WCM or BAM
Beam size	Few µm to few mm	No	Screen or WS
Energy spread	**1e-5** – few per cent	No	Dipole + Screen or WS
Pulse duration	< **1 fs** – ~100 fs	Yes	Compression monitors (rel.) or TDS
Emittance	~**10 nm** to few µm (norm.)	No	Screen or WS
Time-resolved properties	~1 fs in time, the rest as for projected	No	Streaker + screen

Contents

Optics-based emittance measurements

- The 2D (4D) transverse beam matrix is obtained measuring the beam sizes (and <xy>) for different phase advances between reconstruction point s_0 and measurement point s.

4D, 2D:

$$\begin{cases} \langle x^2\rangle_s = R_{11}^2\cdot\langle x^2\rangle_{s_0} + R_{12}^2\cdot\langle x'^2\rangle_{s_0} + 2R_{11}R_{12}\cdot\langle xx'\rangle_{s_0} \\ \langle y^2\rangle_s = R_{33}^2\cdot\langle y^2\rangle_{s_0} + R_{34}^2\cdot\langle y'^2\rangle_{s_0} + 2R_{33}R_{34}\cdot\langle yy'\rangle_{s_0} \\ \langle xy\rangle_s = R_{11}R_{33}\cdot\langle xy\rangle_{s_0} + R_{12}R_{33}\cdot\langle x'y\rangle_{s_0} + R_{11}R_{34}\cdot\langle xy'\rangle_{s_0} + R_{12}R_{34}\cdot\langle x'y'\rangle_{s_0} \end{cases}$$

What we can measure at *s*

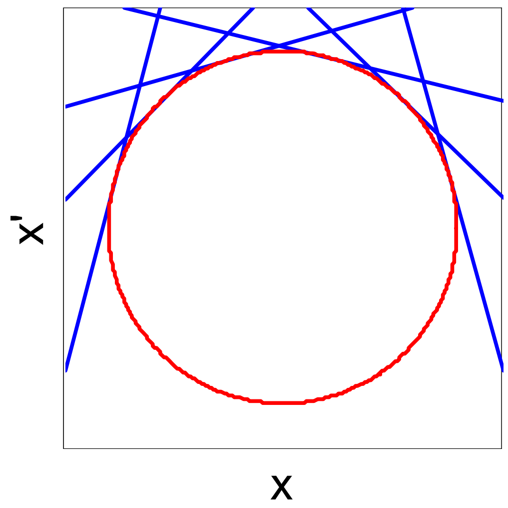
What we want to reconstruct at *s_0*

$$\sigma_{4\mathrm{D}s_0} = \begin{pmatrix} \langle x^2\rangle_{s_0} & \langle xx'\rangle_{s_0} & \langle xy\rangle_{s_0} & \langle xy'\rangle_{s_0} \\ \langle xx'\rangle_{s_0} & \langle x'^2\rangle_{s_0} & \langle x'y\rangle_{s_0} & \langle x'y'\rangle_{s_0} \\ \langle xy\rangle_{s_0} & \langle x'y\rangle_{s_0} & \langle y^2\rangle_{s_0} & \langle yy'\rangle_{s_0} \\ \langle xy'\rangle_{s_0} & \langle x'y'\rangle_{s_0} & \langle yy'\rangle_{s_0} & \langle y'^2\rangle_{s_0} \end{pmatrix} \longrightarrow$$

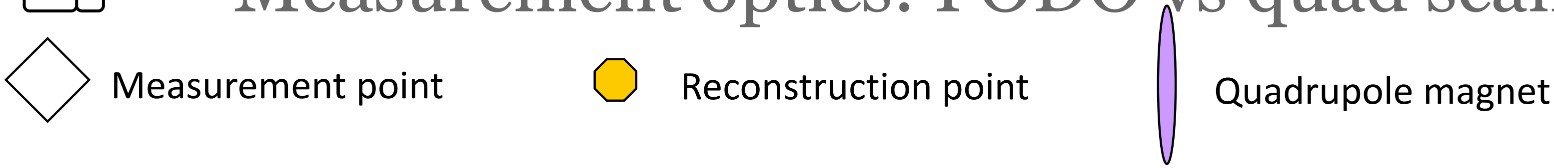
$$\varepsilon_x = \sqrt{\langle x^2\rangle\cdot\langle x'^2\rangle - \langle xx'\rangle^2}$$
$$\beta_x = \langle x^2\rangle/\varepsilon_x$$
$$\gamma_x = \langle x'^2\rangle/\varepsilon_x$$
$$\alpha_x = -\langle xx'\rangle/\varepsilon_x$$

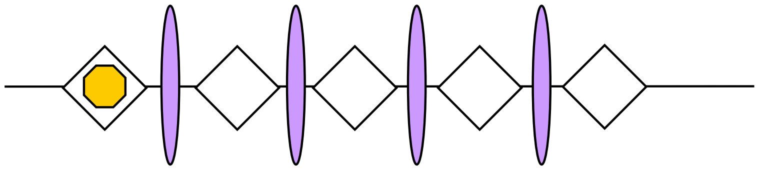
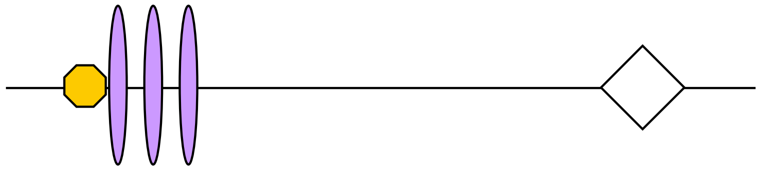
Intrinsic emittances ε_1, ε_2 are derived from 2D and coupling terms *[K. Kubo, ATF Report 99-02 (1999)]*

- At least 3 (4) transformations are needed for 2D (4D) parameters, but more measurements improve the robustness of the reconstruction
- The best 2D reconstruction is when the phase-advance is covered regularly between 0 and π



Measurement optics: FODO vs quad scans

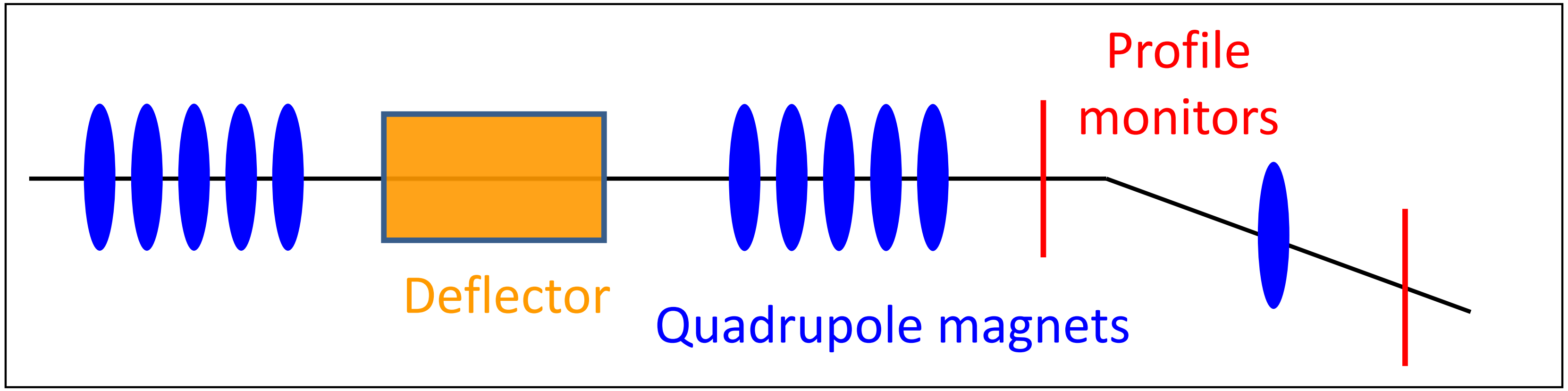


FODO Multiple-position/fixed-optics	*Quadrupole scan* Fixed-position/multiple-optics
	
Parasitic measurements	No parasitic measurements
More equipment	Less equipment
Dedicated long lattices	More compact
Not-flexible optics	Flexible optics
Non-flexible measurement location	Flexible measurement location
Less sensitive to PM errors	More sensitive to PM errors
Typically worse resolution	Better resolution
Larger phase-advance steps	Smaller phase-advance steps

- Quadrupole scans are preferred since they are more flexible, require less components, are more compact and can have better resolutions
- (My) best approach:
  - For commissioning or machine setup: use quadrupole scans at several locations in the machine
  - For routine operation: FODO measurements. Don't allocate dedicated lattices but use what is already there (e.g. long linac sections) → more compact accelerator

Time-resolved measurements

The beam is deflected in one direction as a function of time and the slice parameters in the other direction are reconstructed using **2D profile monitors**.



Profile monitor

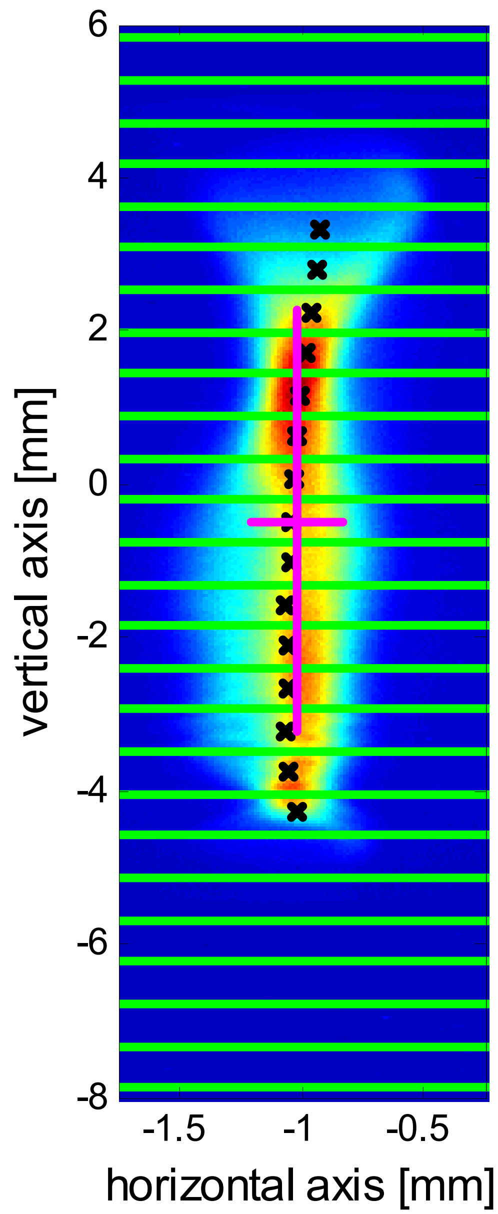
- In straight section: measurement of transverse slice beam properties
- In dispersive location: longitudinal phase-space measurement

Quadrupole magnets

- Used to optimize measurement resolution (emittance, time, energy)
- Quadrupole scan done for emittance measurements
- Fixed optics for longitudinal phase-space measurements

Time-resolved measurements

Image analysis. The beam is split into slices. Per each slice the beam size and centroid are obtained (e.g. doing Gaussian fits).



Emittance/mismatch determination. From the beam sizes per each optics the emittance and optics are obtained per each slice

Beam tilt determination. From the slice trajectory at each optics, the tilt in offset (<xs>) and angle (<x’s>) are obtained

Energy spread: obtained from beam size at dispersive location

Streaking methods

Streaking can be done with different methods:

- Transverse deflecting RF structure (TDS) – more standard method
- Introducing dispersion to an energy chirped beam
- Transverse wakefields

Shared problem: streaking is invasive (unless used after the undulator)

Shared advantage: streaking can be used to shape the FEL beam (short pulses)

	TDS	Dispersion	Wakefields
Demonstrated res.	< 1 fs (*)	~1 fs (**)	~1 fs (***)
Pros	Easy reconstruction	Zero cost	Self synchronized, moderate cost
Cons	High cost, arrival time sensitivity	No absolute measurement. Linear streaking only if linear energy chirp.	Nonlinear streaking, difficult reconstruction

(*) *[C. Behrens et al, Nat. Comm. 5, 3762 (2014)]*
(**) *[E. Prat et al, PRR 4, L022025, 2022]*
(***) *[P. Dijkstal et al, PRR 4, 013017 (2022)]*

The methods can be combined for enhanced resolution!

Contents

Some important resolutions

	Resolution (*)	Required resolution	Optics strategy	Required PM resolution
Emittance	$\dfrac{\sigma_R^2 E}{m_e c^2 \beta}$	~10 nm	Increase β at the screen	~5 µm (e.g. β=50m, E=10 GeV)
Time	$\dfrac{\sqrt{\sigma_R^2 + \frac{m_e c^2 \beta \epsilon_n}{E}}\, E}{\sqrt{\beta_T \beta}\, \sin(\mu)\, eVck}$	~1 fs	Increase β at the deflector and at the screen, make $\sin(\mu)$ ~ 1	~10 µm (e.g. β=β_T=50m, $\sin(\mu) = 1$, ϵ_n=200 nm, E=10 GeV, V=100 MV, C-band)
Energy spread	$\dfrac{\sqrt{\sigma_R^2 + \frac{m_e c^2 \beta \epsilon_n}{E}}}{D}$	<1e-5 (1 keV for 100 MeV)	Decrease β and increase dispersion (D) at the screen	~10 µm (e.g. D=1.5 m, β=0.1m, ϵ_n=200 nm, E=100 MeV)

- Optics should be optimized for each particular resolution
- For all cases, improve the screen resolution helps
- Most critical case is emittance resolution (we can increase streaking for time resolution, and dispersion for energy spread resolution) →

→ **around 5 µm required** for 10 nm resolution

(*)This standard resolution can be overcome by measuring the properties for different parameters (e.g. energy)

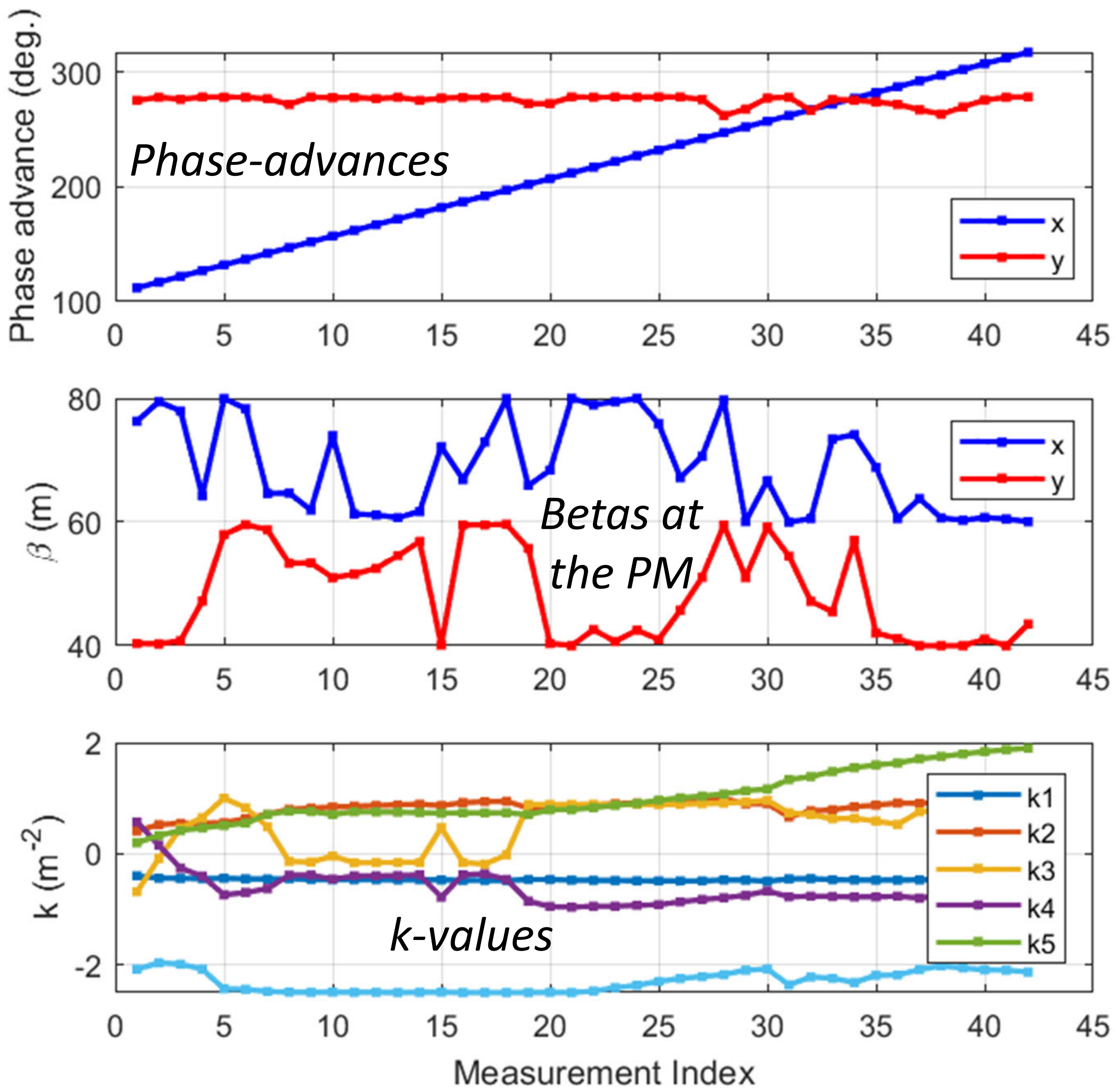
Optimized multiple-quadrupole scan for slice emittance measurements

Example for SwissFEL

Beta at the TDS in the streaking plane is 60 m (for good time resolution)

Six quadrupoles between TDS and PM are used to:

- Optimize emittance resolution:
  - Scan regularly phase advance in measurement plane
  - Large beta at the screen in the measurement plane
- Optimize time resolution:
  - sinμ~1
  - Large beta at the PM in the streaking plane



Some words on profile monitors

- The devices commonly used to measure the transverse beam parameters in FEL facilities are OTR screens, scintillator screens (e. g. YAG), and wire-scanners.

	Scintillator screens	OTR screens	Wire-scanners (WS)
Demonstrated resolution	15 μm w/o MO (*) 5 μm with MO (**)	(As good as scintillators)	0.5 μm (***)
2D information (slice, coupling, tilts)	Yes	Yes	No
Charge sensitivity	Very good	Poor	Very good
Measurement time	Fast	Fast	Slow
Interference with operation	Yes	Yes	Less
Issues	Saturation effects	COTR	Multi shot measurement (jitter correction required)

- WS have the best resolution, but 2D information is missing – and they are slow.
- Scintillators are better than OTRs, a MO is required for few-μm resolution

MO = microscope objective.
(*) *[R. Ischebeck et al, PRSTAB 18, 082802 (2015)]* Scintillator thickness was 100 μm
(**) *[J. Maxson et al, PRL 118, 154802 (2017)]* Scintillator thickness was 20 μm
(***) *[S. Borrelli et al, CP 1, 52 (2018)]* Use of sub-μm metallic stripes on a membrane using lithography, standard WS have a resolution of 1.25 μm

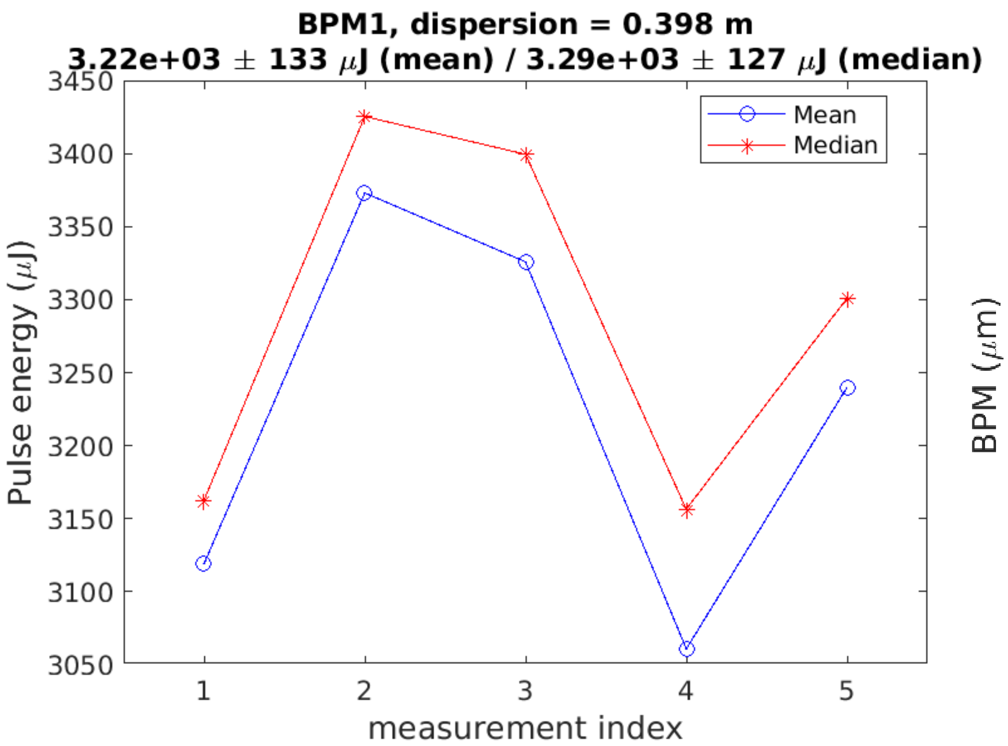
PAUL SCHERRER INSTITUT

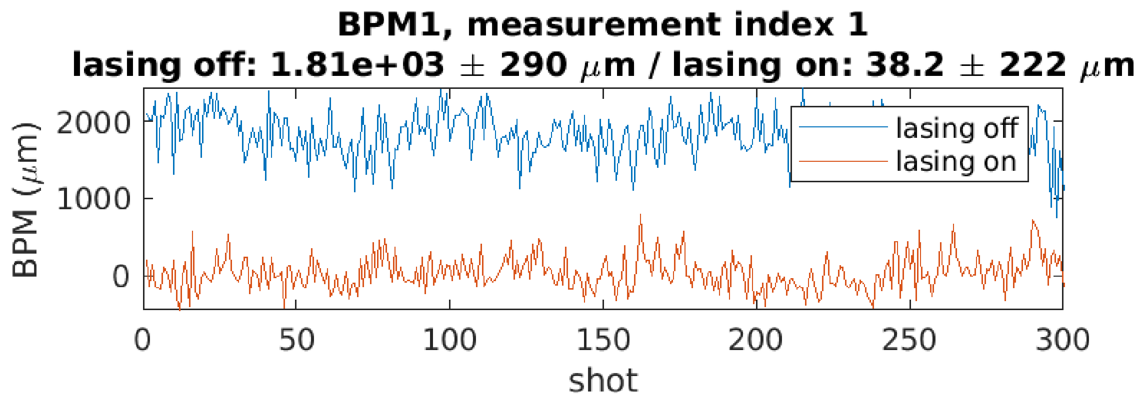
Contents

- Electron beam requirements for X-ray FELs
- Electron beam instrumentation requirements
- Emittance and time-resolved measurements
- Some important resolutions, implication to optics and transverse profile monitor (PM) resolution
- FEL properties from electron beam properties
- Summary and conclusion

FEL properties from electron beam properties

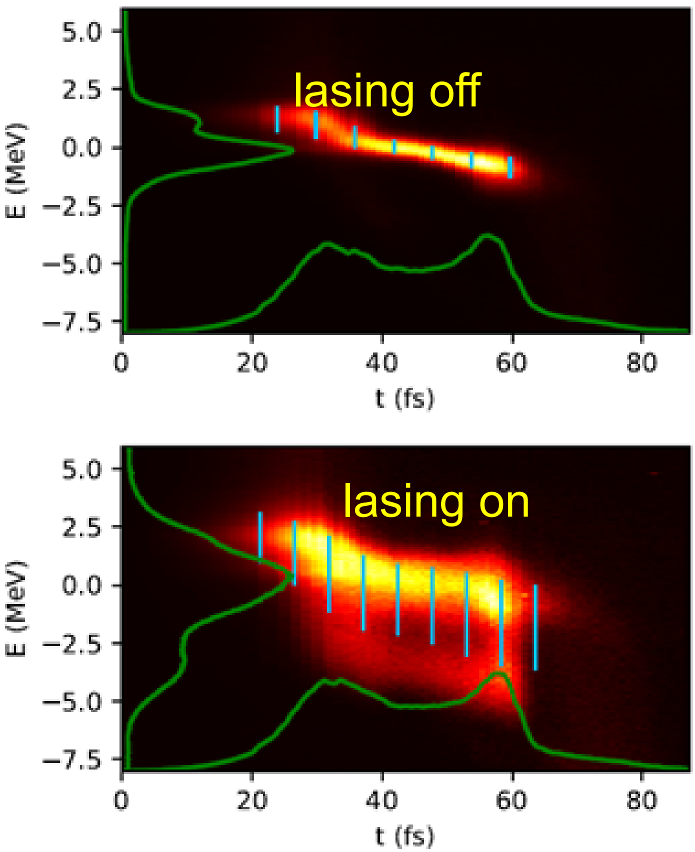
- FEL process reduces the energy and increases the energy spread of the electrons
- Comparing the energy loss and energy spread increase of the electrons between lasing-on and lasing-off conditions is useful to diagnose the FEL pulse energy and the FEL power profile.
- FEL pulse energy: we just need a BPM in a dispersive section. Useful to calibrate photon gas detector



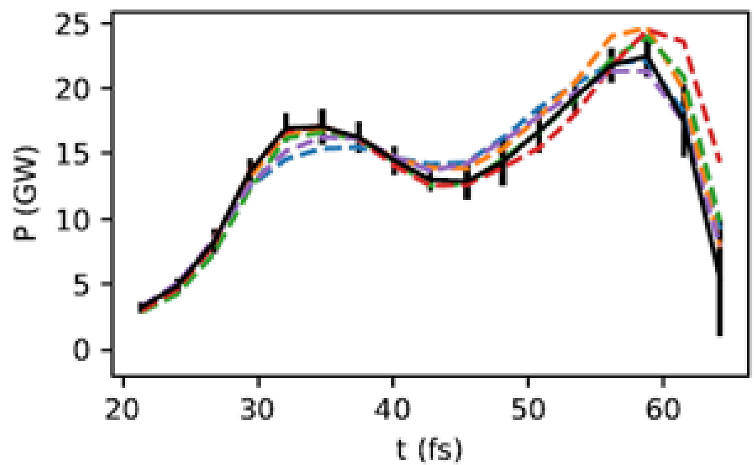


FEL properties from electron beam properties

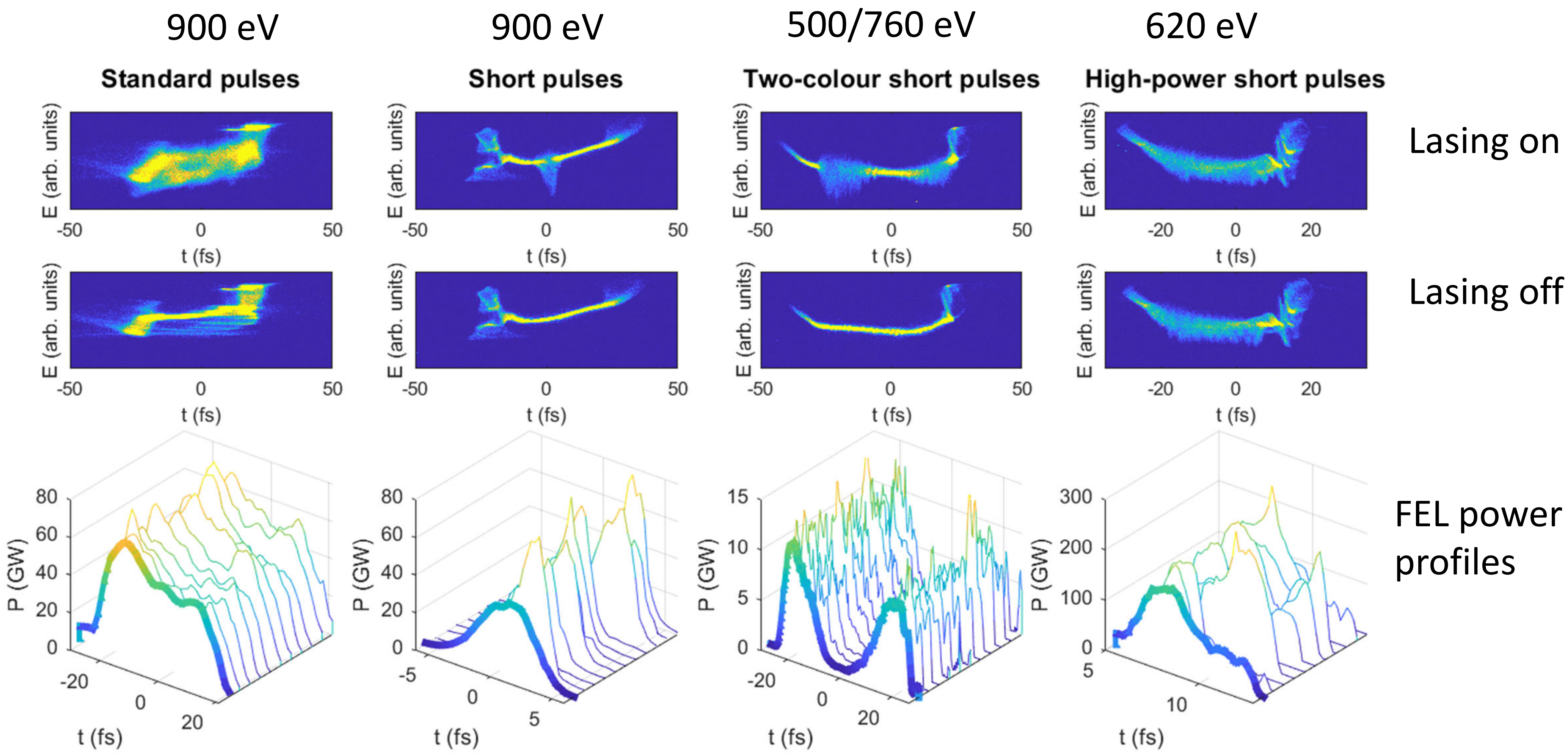
- FEL power profile: we need a TDS and a screen in a dispersive section to measure the longitudinal phase-space (some limitations like slippage effects)
- Method originally proposed in *[Ding et al, PRSTAB 14 120711 (2011)]*, first demonstrated in *[Behrens et al, Nat. Comm. 5, 3762 (2014)]*



Example with a passive streaker
[Dijkstal et al, PRR 4, 013017 (2022)]



Examples at SwissFEL



- Measurement: streaking with X-band + dispersion tilt (short pulse cases)
- Power profile from energy spread increase due to lasing
- Time resolution better than 1 fs

Contents

- Electron beam requirements for X-ray FELs
- Electron beam instrumentation requirements
- Emittance and time-resolved measurements
- Some important resolutions, implication to optics and transverse profile monitor (PM) resolution
- FEL properties from electron beam properties
- Summary and conclusion

Summary and conclusion

- In X-ray FELs, electron beam diagnostics should measure:
  - Trajectory with <1 µm trajectory
  - Normalized emittances with ~10 nm resolution
  - Energy spreads with < 1e-5 resolution
  - Time-resolved properties with < 1 fs resolution
  - (Radiation-loss monitors)

- Optics should be optimized for best resolutions… but anyway we need PMs with resolutions of 10 µm or better

- Energy and longitudinal phase-space measurements of the electron beam should be used to reconstruct FEL pulse energy and power profile.

- State-of-the-art diagnostics almost sufficient to cover the requirements. Possible improvements in standard facilities:
  - Hardware: screens with few µm resolution, streaking devices with < 1 fs resolution
  - Reduce invasiveness of some diagnostics → machine learning?