Paolo Craievich :: RF section :: Paul Scherrer Institut

State-of-the-art active TDS (TDC, XTCAV…) systems for time resolved diagnostics

LEDS, ENEA Frascati, 3-5 October 2023

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Outline

– Motivations for high-resolution time-resolved diagnostic

– TDS as diagnostic tools

– News from LCLS, a new XTCAV

– Novel Concept with Variable Polarization – The PolariX TDS

– The MAX IV TDS system

– Post-undulator PolariX TDS for ATHOS

- ❖ Specifications and commissioning
- ❖ Results

– Outlook and conclusion

Motivations for high-resolution time-resolved diagnostics

Ongoing Tendency of Getting Shorter and shorter Electron Bunches

- FEL science (users): novel coherent diffractive imaging techniques and timing of ultrafast process require shorter (sub-fs/as) FEL X-ray pulses
  - Sub-fs-level temporal resolution are required for the optimization of the electron bunches
  - Single-shot characterization of the longitudinal phase space of the electron beam allows for single-shot reconstruction of the photon pulses as well
- Novel high-gradient acceleration techniques (LWFA, PWFA, THz driven Acceleration, DLA) are characterized by short period of accelerating field and therefore naturally produce or accelerate fs long bunches
  - The focusing gradients (inherent) to these novel high-gradient accelerator concepts require high-quality, axially-symmetric bunches
  - Longitudinal characterization of the driver and witness electron beams is essential for characterizing and optimizing the acceleration channel

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Transverse Deflecting Structures – What’s next?

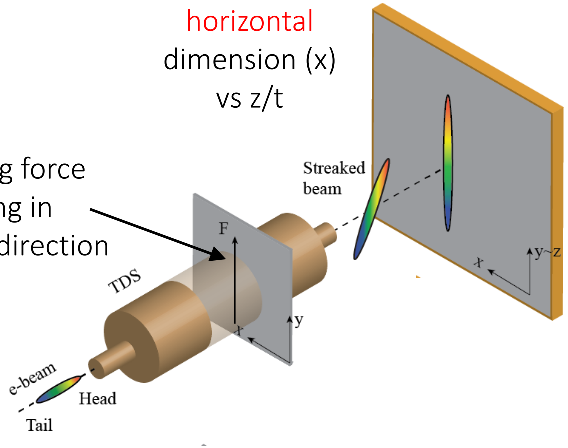
TDS are RF-based devices used for the manipulation and/or the diagnostics of charged particle beams to retrieve longitudinal/temporal proprieties

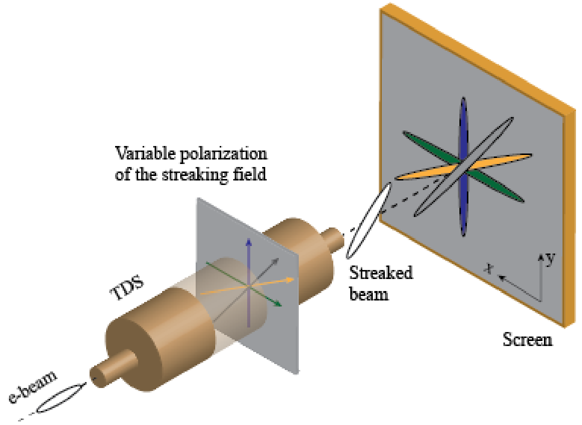
Conventional TDS: streaking in a fixed polarization (i. e. vertical or horizontal)

POLARIzable X-band Transverse Deflection Structure – **POLARIX TDS**

horizontal dimension (x) vs z/t

Streaking force oscillating in vertical direction





The longitudinal distribution of the e-bunch is mapped into the transverse one thanks to the time dependent transversely deflecting field

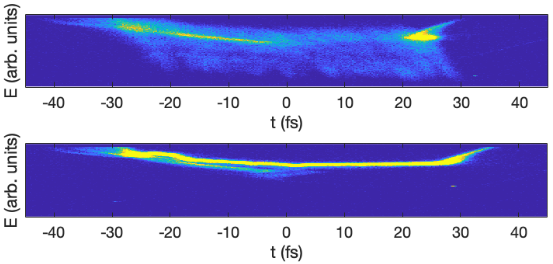
Diagnose multidimensional phase space of electron bunches to investigate complex beam dynamics (e.g. collective effects, beam correlations, slice emittance..)

TDS as diagnostic tools – capabilities

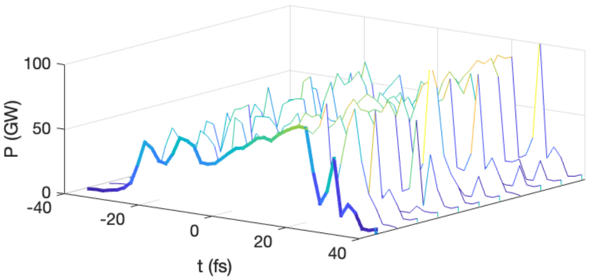
- Bunch length and longitudinal charge profile measurements (1D)
- Combined with dipole spectrometer → longitudinal phase space measurement
- Combined with quadrupole scan or multi-screen lattice → slice emittance measurement on the plane perpendicular to the streaking direction, slice transverse phase space reconstruction - **slice emittance on different transverse planes**
- Measurement of the FEL-induced lasing effects imprinted on the electron beam longitudinal phase space: first reference C. Behrens et al., Nat. Comm. 5, 3762 (2014)
- 5D/6D phase-space characterization becomes possible by different streaking planes and using tomographic methods

FEL ON

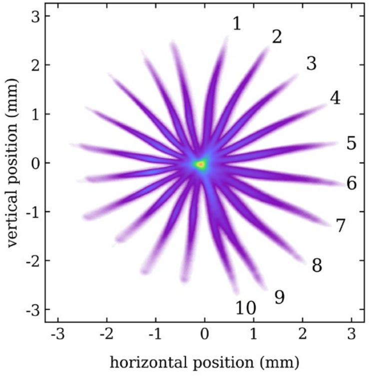
FEL OFF



Example from SwissFEL/Athos



Photon pulse profile



B. Marchetti et al., Sci. Rep., 2021

TDS as a diagnostic tool – time resolution

Longitudinal resolution is limited by the vertical beam size and the streak parameter S:

$$\sigma_{t,R} \geq \frac{\sigma_{y0}}{S} = \sqrt{\frac{\varepsilon_{N,y}}{\gamma \beta_d}} \frac{pc}{eV_\perp \, ck_{rf}} \frac{1}{\sin(\Delta\psi_{ds})}$$

Given by the project

Electron bunch: ✓
- beam energy
- normalized emittance $\varepsilon_{N,y}$ (screen resolution!!)

Optics:
- phase advance, $\sin(\Delta\psi_{ds})$
- beta function at TDS, β_d

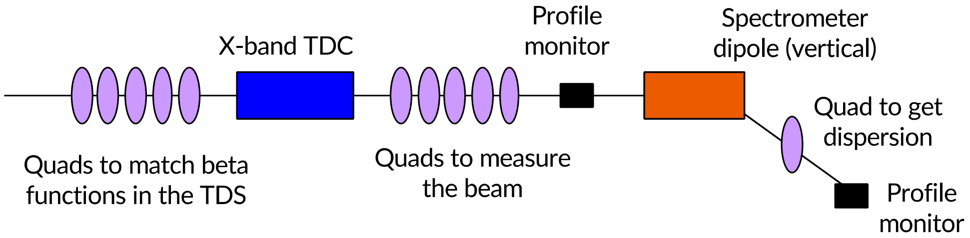
✓ Optic design of the diagnostic beam line
✓ $\sin(\Delta\psi_{ds}) \sim 1$
✓ High-beta function at TDS

RF structure:
- wave number $k_{rf} = w_{rf}/c$
- Integrated deflecting voltage $V_\perp = \mathrm{K} \cdot \mathrm{L} \cdot \sqrt{P_{RF}}$

✓ X-band frequency allows having higher resolution due a smaller wave number than S-band (x4) and C-band (x2) frequencies
✓ Shorter structure with large kick

TDS as a diagnostic tool – some remarks

General measurement concept



TDS system needs space for the installation of all components!

Energy resolution

Off-axis particles are also accelerated $V_z(y) = k*y*V_0$
This results in a relation of time and energy resolution:

$\delta_E \sigma_z = \varepsilon$ (C. Behrens and C. Gerth, DIPAC09)

$$\sigma_{\Delta Eind} = \frac{E_0 \cdot \varepsilon_N}{c \cdot \sigma_{t,res}}$$

More info:
E. Prat et al. PR AB 23, 090701 (2020)

Time resolution

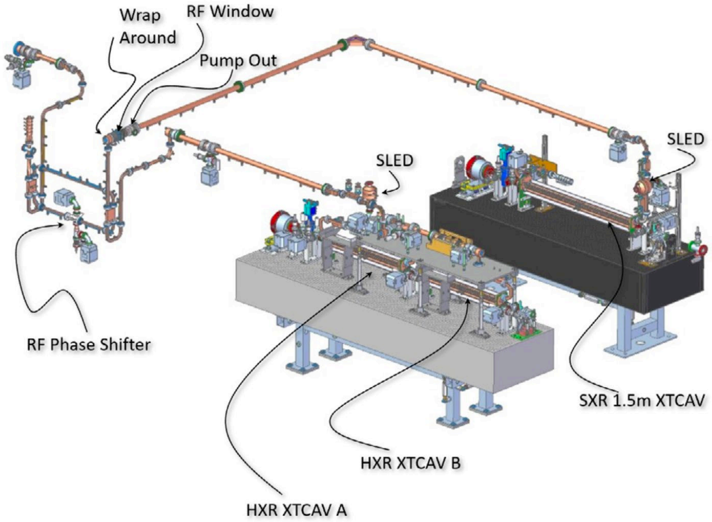
The time resolution is limited because of RF phase jitter

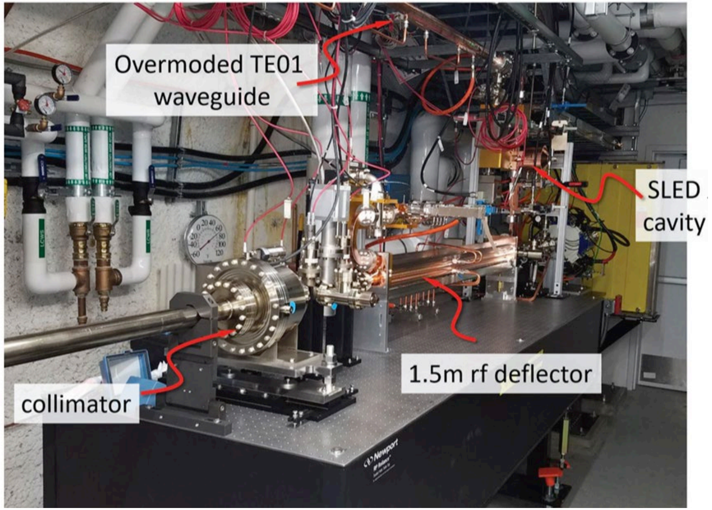
- An RMS phase jitter of ~0.05° in X-band is adequate for measurements during setup or commissioning, but a peak-to-peak of ~0.5° causes the beam to collide with the vacuum chamber → beam-loss monitors can be triggered, interrupting user operation.
- Without a solution to reduce phase jitter, there is a tendency in operation to keep the RF power below its maximum amplitude and operate at a lower repetition rate.

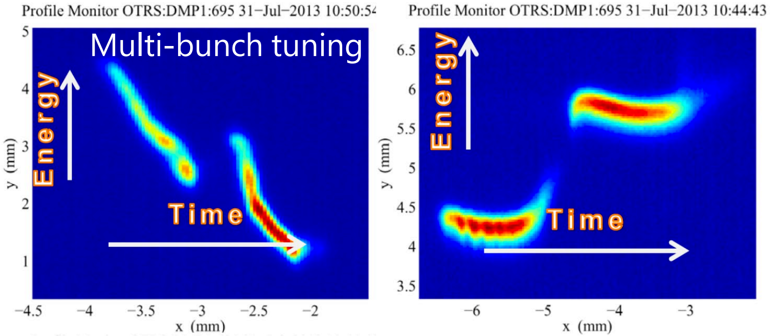
The XTCAVs at the LCLS HXR and SXR

References: V. Dolgashev et al., IBIC 2021 and P. Krejcik, FLS 2023

Parameter	HXR	SXR	Units
Beam Energy	4-14	4-10	GeV
Beam emittance	0.5	0.5	µm
Structure length (with beam pipes)	2 × 1.185	1.657	m
Number of regular cells (including joining ring)	2 × 113	171	
Input power	70 + 70	70	MW
On-crest deflecting voltage	80	60	MeV
Resolution achieved	0.5-2	1-4	rms fs
Distance deflector-screen	32	32	m
Beta functions at RF deflector	80@8 GeV	80@8 GeV	m
Beta functions at the screen	63@8 GeV	55@8 Gev	m

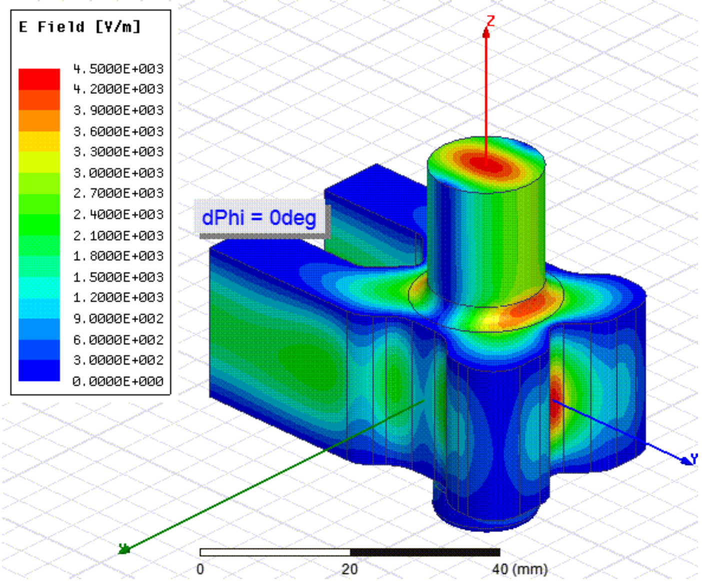






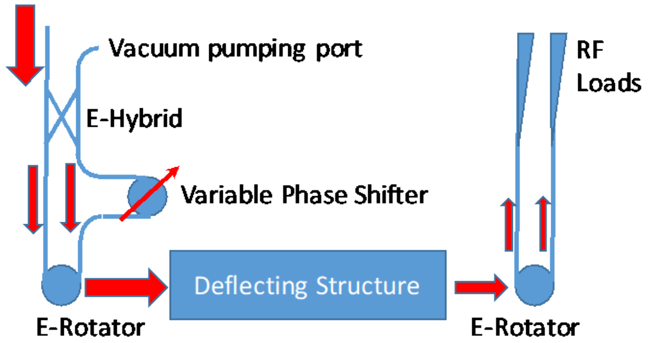
Novel Concept with Variable Polarization – X band

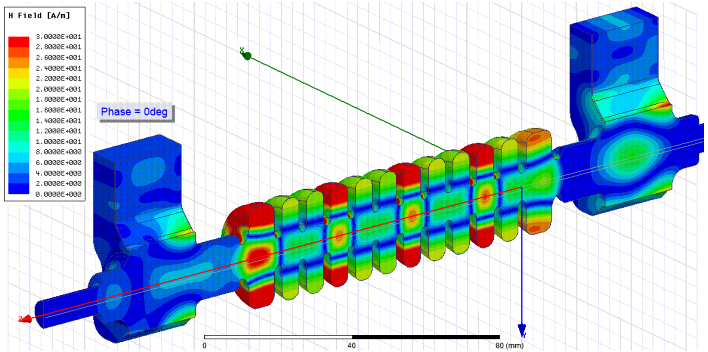
Variable polarization circular TE11 mode launcher: E-rotator



Phase difference between port 1 and port 2:

- 0 degree -> vertical polarization
- 180 degree -> horizontal polarization





References:

Grudiev, CLIC-Note-1067, 2016
P. Craievich et al., Phys. Rev. Accel. Beams, 2020
B. Marchetti et al., Sci. Rep., 2021

DESY-CERN-PSI Collaboration

History of the Collaboration, including the main Milestones of the Project

The RF design of the TDS has been done at CERN (with support from PSI)

Common Mechanical Design of the structure fulfilling the requirements of the different experiments.

The mechanical design of the prototype has been done at PSI. The prototype as well as the series structures has been manufactured using the PSI tuning free assembly procedure.

CERN performed the high-power test of the prototype.

DESY installed the prototype structure and appropriate RF-source in the FLASHForward beamline for first test of the structure with electron-beam → this lead to first measurements in September 2019!

2x TDSs installed in FLASH II and in operation

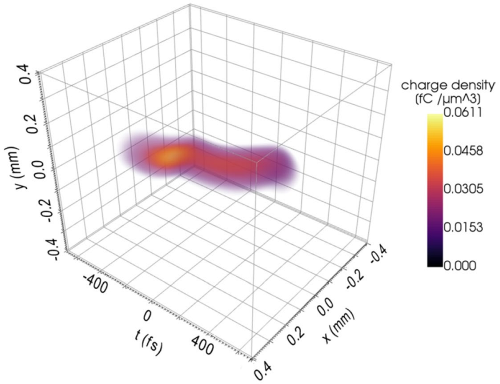
2x TDS installed in SINBAD-ARES (DESY) – they will start the RF conditioning soon

2x TDSs installed in SwissFEL Athos

Variable streaking angle enables new tomographic methods

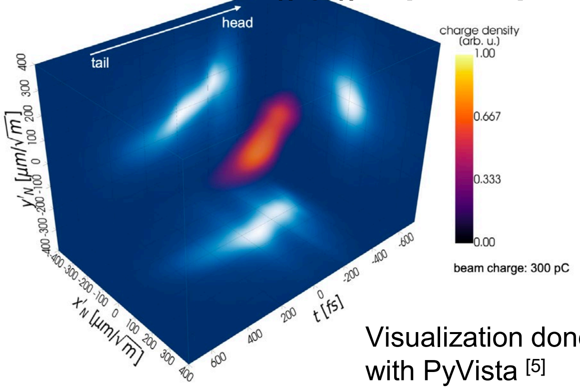
To obtain the full 5-dimensional (x, x′, y, y′, t) phase space of bunches

Experimental reconstruction of 3D charge density [1, 2] at FLASHForward:



Successful reconstruction of the 5D phase-space distribution

3D visualization of the (x'_N, y'_N, t) phase space



Visualization done with PyVista [5]

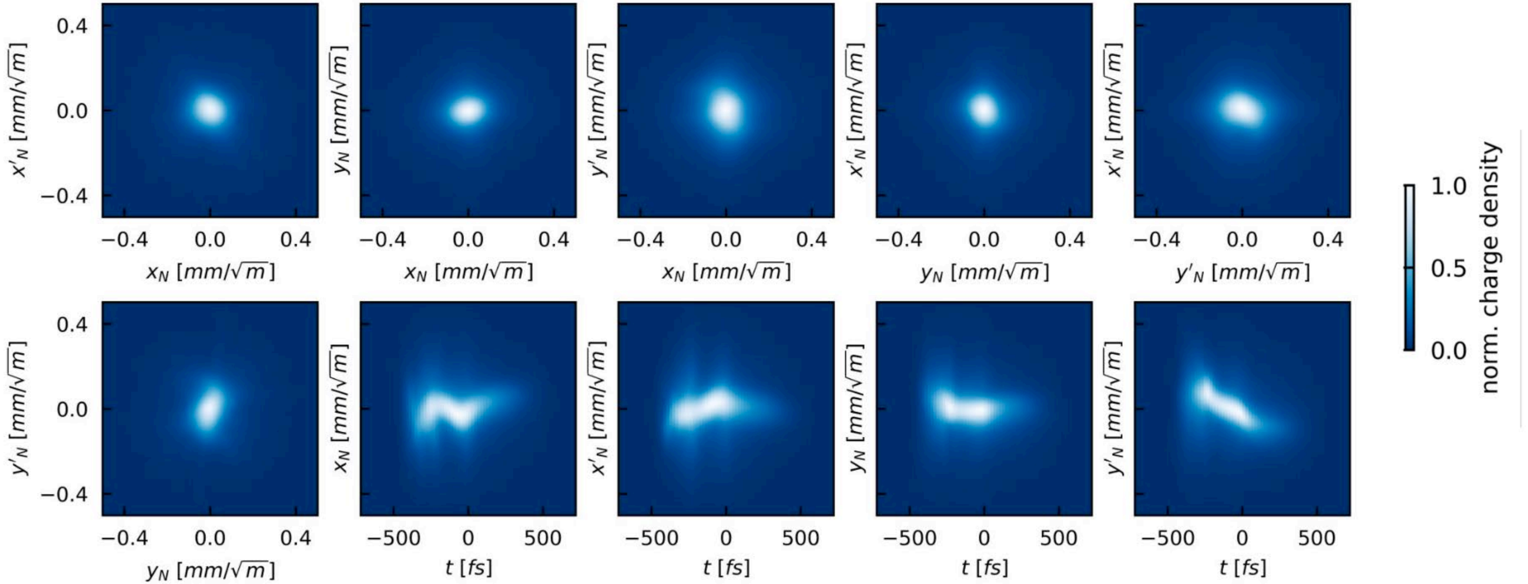
- 5D tomography: Quadrupole-based transverse phase-space tomography + streaking along various angles with PolariX TDS.
- Excellent performance shown in simulations [3, 4].
- Experimentally demonstrated (Sonja Jaster-Merz, IPAC’23, WEODB2)

[1] D. Marx et al., Journal of Physics: Conference Series, vol. 874, 2017,
[2] B. Marchetti et al., Sci. Rep., 2021 ,
[3] S. Jaster-Merz et al., JACoW IPAC2022 MOPOPT021, 2022 ,
[4] S. Jaster-Merz et al., JACoW LINAC2022 MOPORI10, 2022,
[5] Sullivan and Kaszynski, Journal of Open Source Software, 2019

Slide courtesy of S. Jaster-Merz DESY.

Reconstructed 5D phase space enables new insights

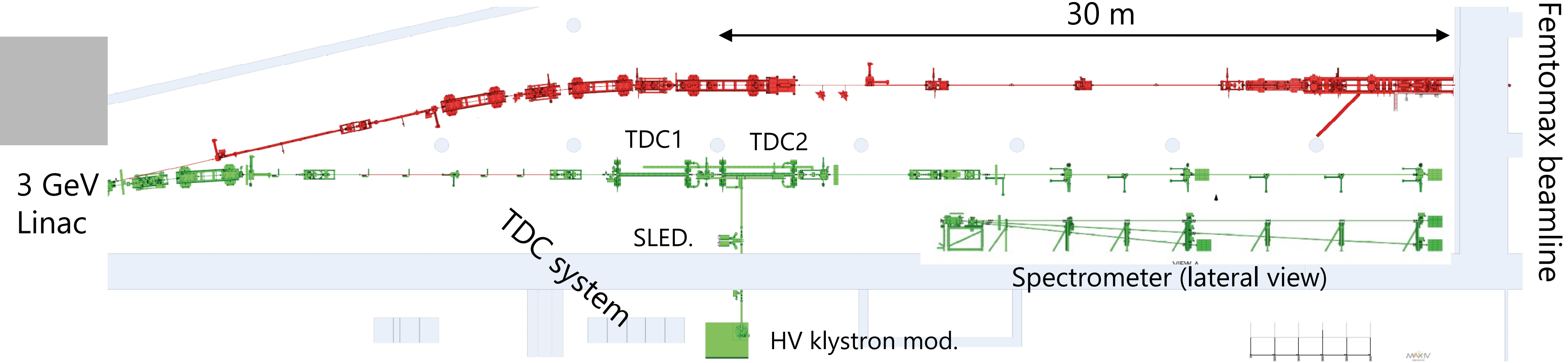
5D phase-space reconstruction of an electron beam - WEODB2 | Sonja Jaster-Merz, IPAC’23



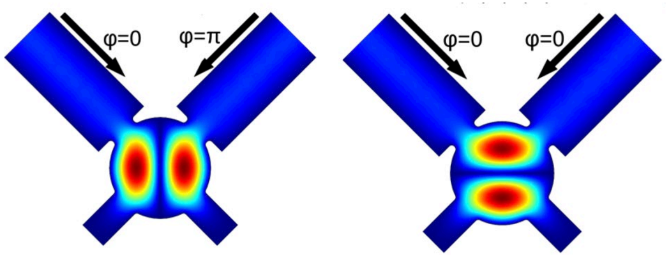
- **All 2D projections** of the 5D phase space, and **sliced** 4D emittance.
- **Full 5D** phase-space distribution enables improved modelling of accelerators, benchmarking of simulation codes.

The MAX IV TDS systems (variable polarization)

Courtesy of Erik Mansten (MAX IV) - IBIC 2023



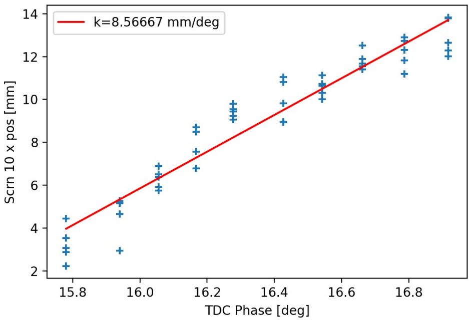
- S-band frequency and standard MAX IV HV klystron modulator (K2 + SLED)
- Integrated voltage >100 MV with 2x RI 3-m long TW TDC
- Long setup with large beta function at TDCs (>1000m)
- Target time resolution 1 fs
- Variable polarization with phase shifters (phase II)

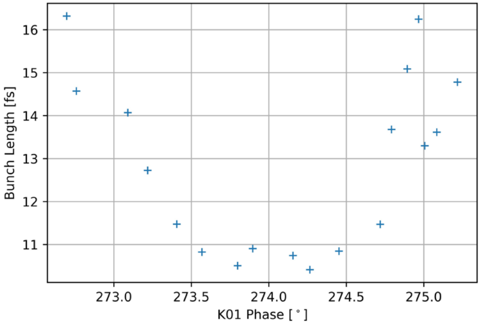


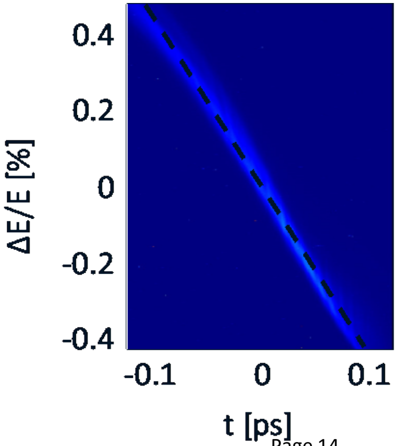
Different approach for the couplers (reference D. Olsson)

The MAX IV TDS systems – Status

- Time resolution 3 fs
  - Current streaking parameters 8 mm/ps → Target 30 mm/ps
    - RF conditioning ongoing, SLED tuning to be verified
- Scan of the compression including linearization at the spectrometer
- Next steps:
  - Slice Twiss parameter scans (slice emittance measurements)
  - More robust RF phase measurements



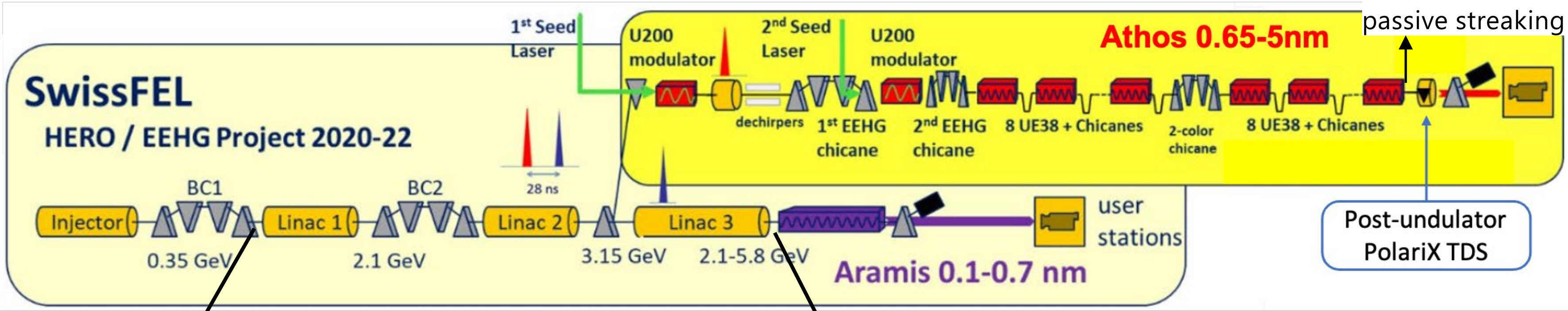




Courtesy of Erik Mansten (MAX IV) - IBIC 2023

Overview of the LPS measurements in SwissFEL

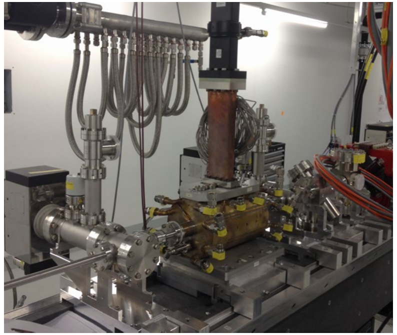
Post-undulator passive streaking

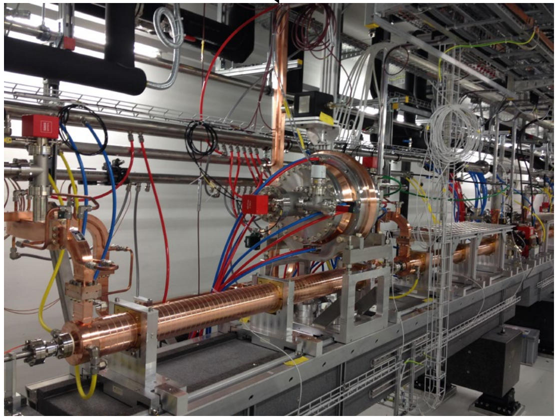


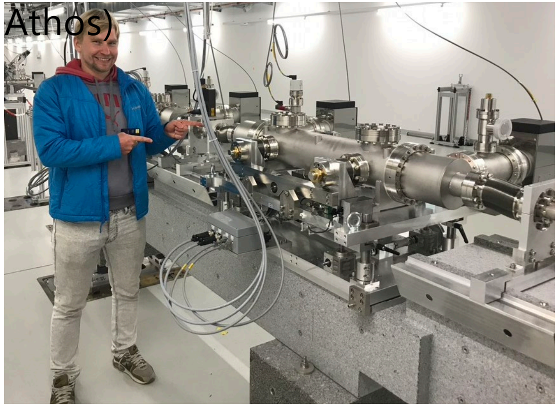
S-band TDS (5-cell SPARC/FERMI/PSI type)

C-band TDS

Post-undulator passive streaking in Aramis (and in Athos)





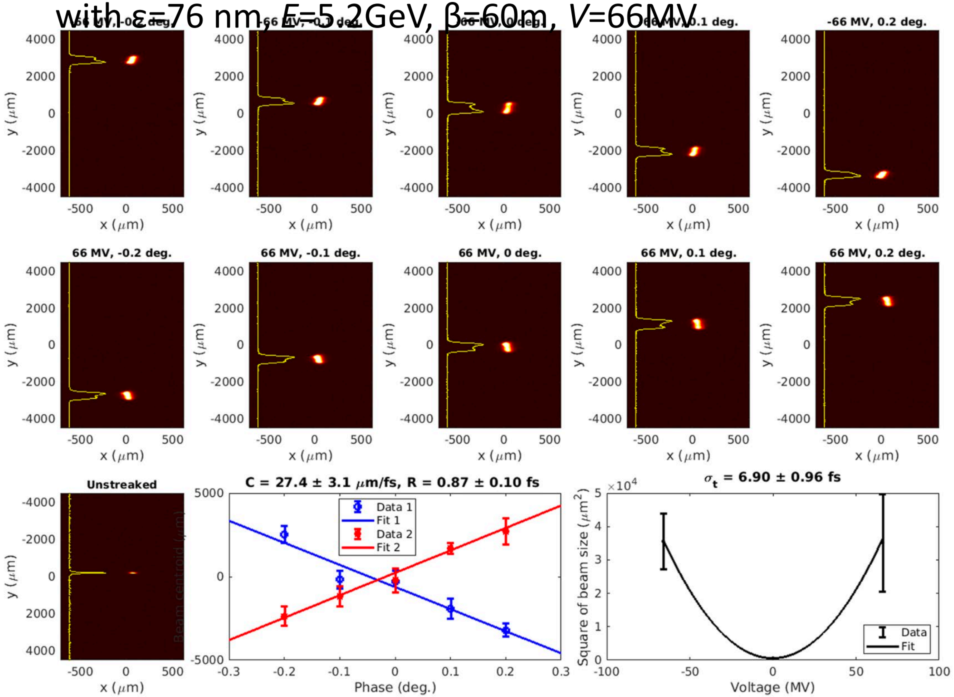


Max integrated Deflecting voltage 5 MV, beam energy 300 MeV, Resolution ~10 fs

C-band TDS system

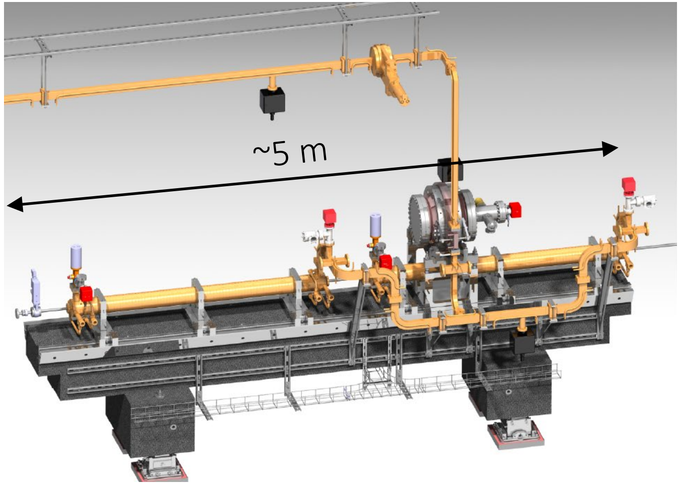
Temporal resolution 0.87 ± 0.10 fs (bunch length 6.90 fs)

with ε=76 nm, *E*=5.2GeV, β=60m, *V*=66MV



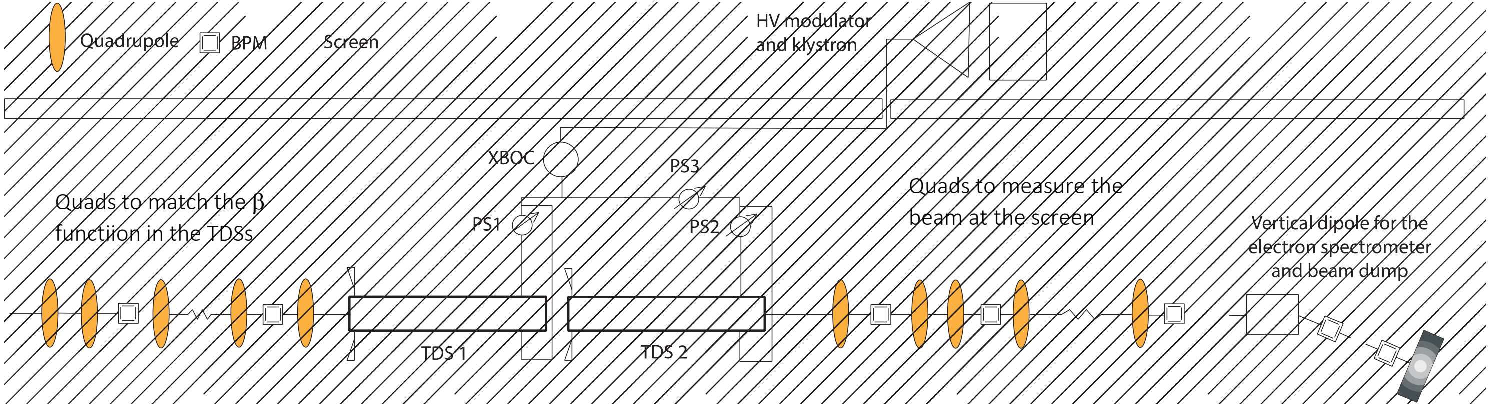
RF system

2x TDSs + BOC		
BOC Q_0	216 000	
BOC β	10	
RF pulse length	3	μs
Power-to-voltage	15.42	MV/MW$^{0.5}$

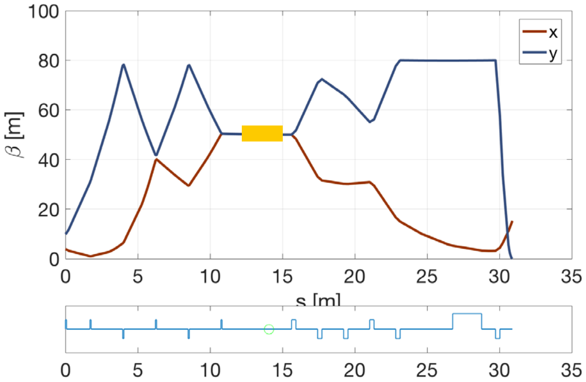


E. Prat, A. Malyzhenkov and P. Craievich, Rev. Sci. Instrum. **94**, 043103 (2023)

PolariX TDS diagnostic beamline @3GeV



$\beta_x = \beta_y = 50$ m → **optics for both polarizations**

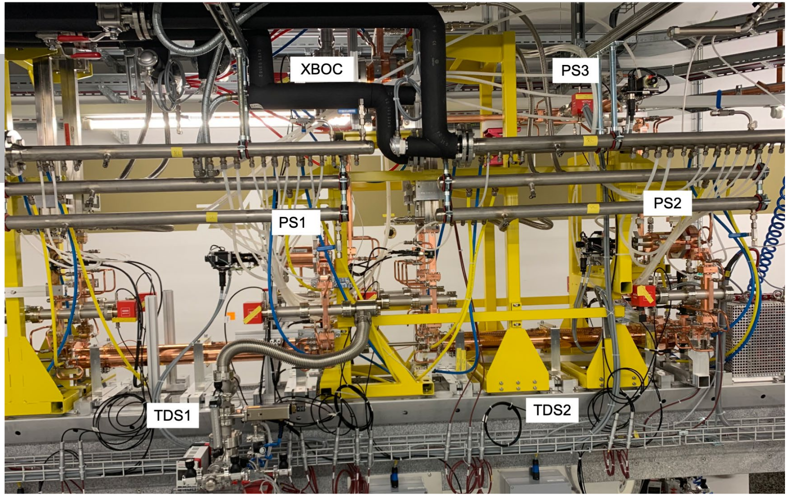


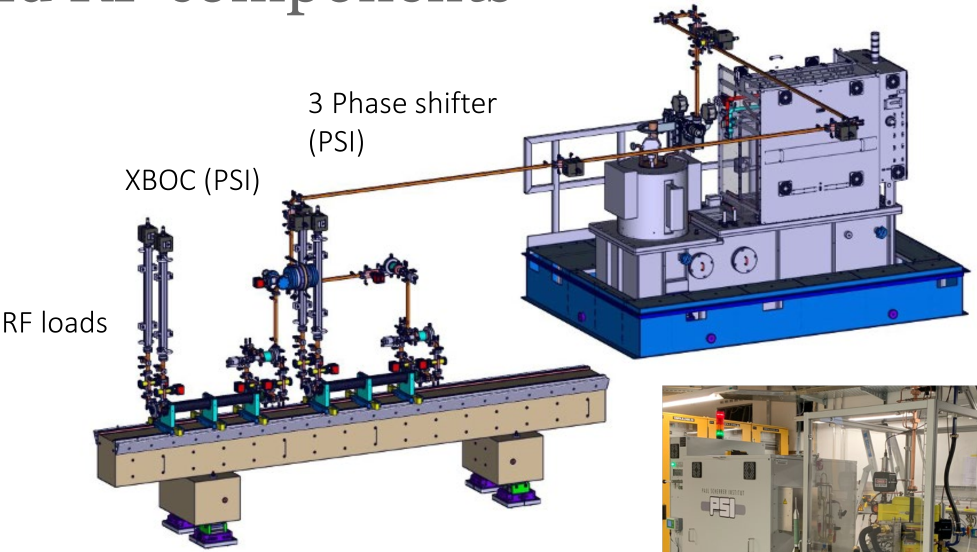
Plot by E. Prat

Beam measurements:

- Projected and slice emittance on different planes
- Electron pulse length and charge density profile (sub-fs resolution)
- Energy spread induced by FEL process (photon pulse length)

X-band TDS and RF components



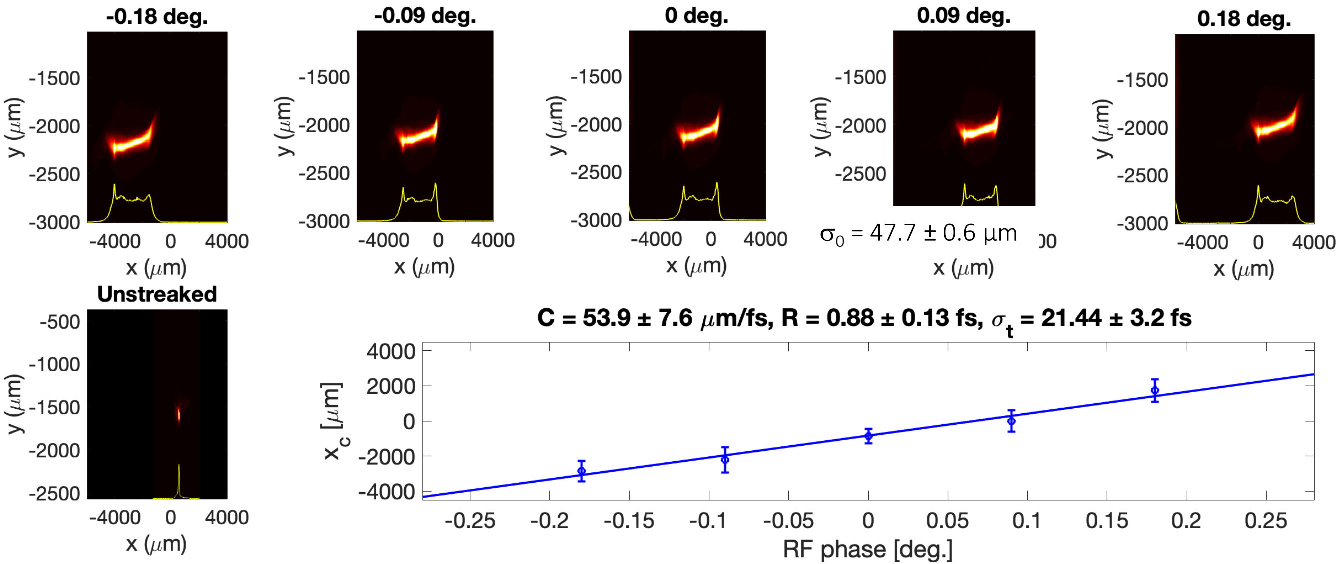


All waveguide RF components including the XBOC and phase shifters were designed and built at PSI, Klystron: CPI VKK-8311, 50 MW X-band

PSI HV modulator: develop and built in-house (400 kV, 3 μs) – stability below 10 ppm

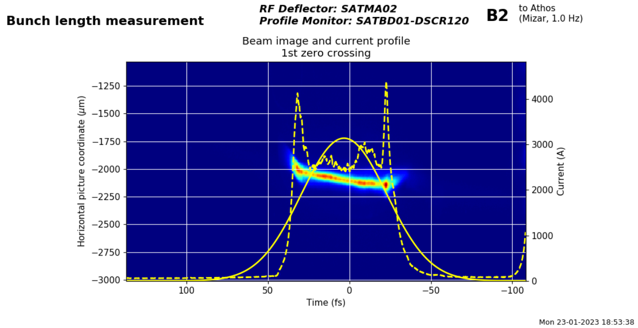
After about three weeks of integrated conditioning time, a peak power from the klystron of 30 MW with a total RF pulse length of 1.0 μs was achieved, now we can run the station with 35 MW with 1.2 us → deflecting voltage higher than 90 MV (specification was higher than 60 MV)

Calibration, resolution and bunch length



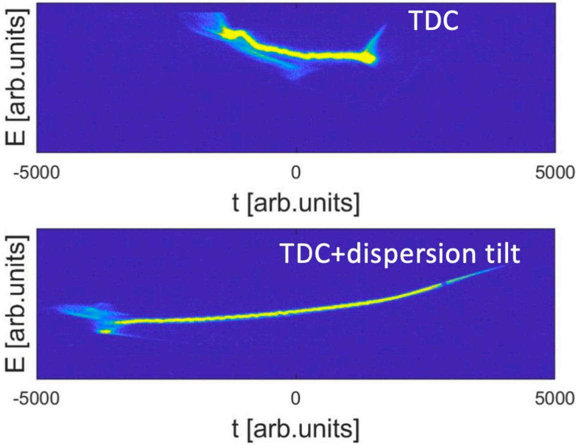
Deflecting voltage 85 MV,
s_0 = 47.7 ± 0.6 μm

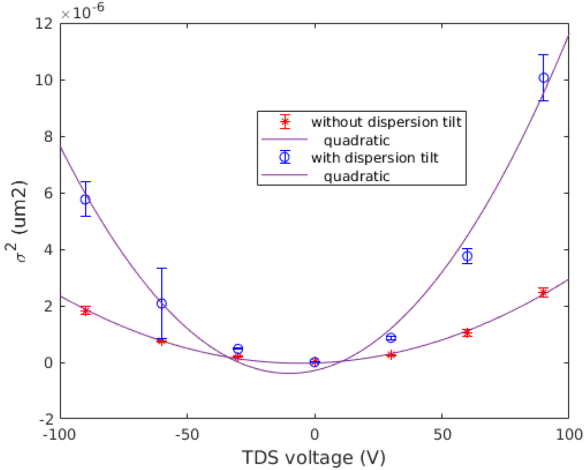
$\sigma_{t,R} = \sigma_0 / C = 0.88$ fs



- Absolute calibration factor C: transverse position of the centroid of the streaked beam against the RF phase
- Time coordinates are obtained by dividing the transverse coordinates on the screen by the calibration
- Bunch length is simply obtained as the streaked beam size divided by the calibration factor C

Streaking combined with dispersive tilt





TDS adds up to the incoming tilt so that the final streaking becomes larger

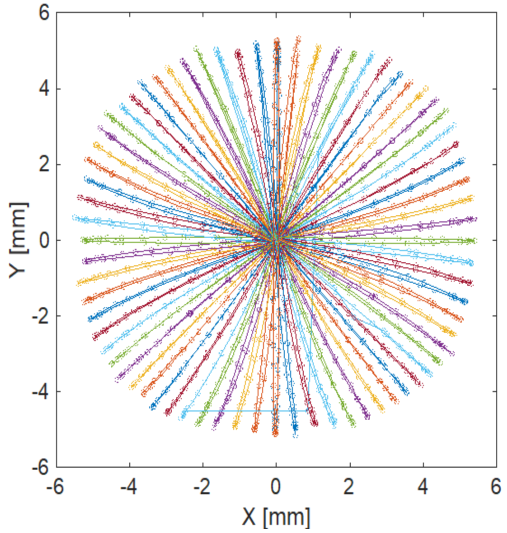
Assuming that the calibration factor does not change with respect to the standard case without initial beam tilt

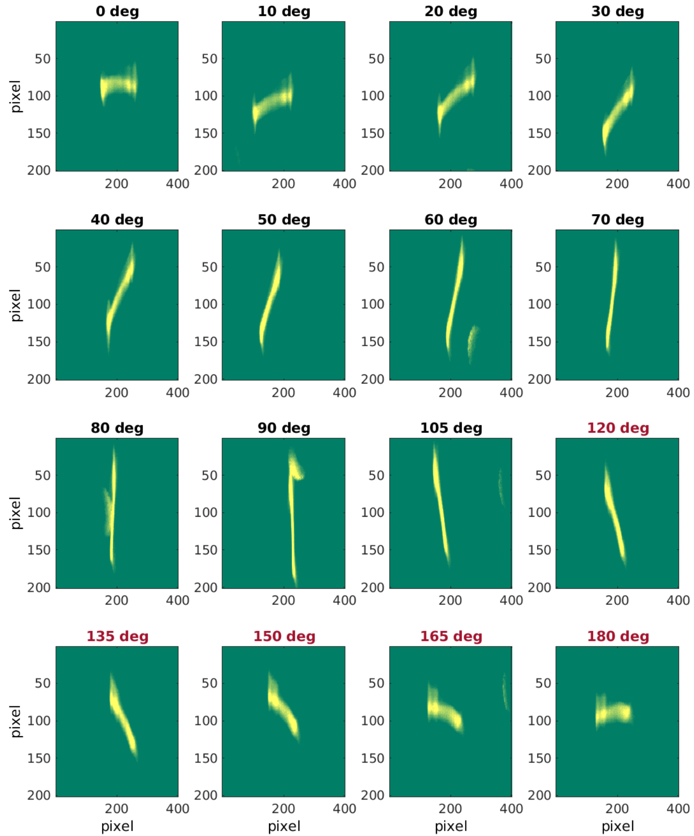
- Measurements after the undulator at the Athos dump (dispersive in Y, streaking in X)
  - Streaking with X-band transverse-deflector cavity (TDC) and dispersion
  - With dispersion, streaking increases by a more than a factor of 2 → resolution < 500 as (?)
- Comparing lasing on and off conditions → FEL power profile reconstruction
  - Post undulator LPS measurements are fundamental to setup and optimize the scheme

Courtesy of E. Prat et al.

Variable polarization – first measurements

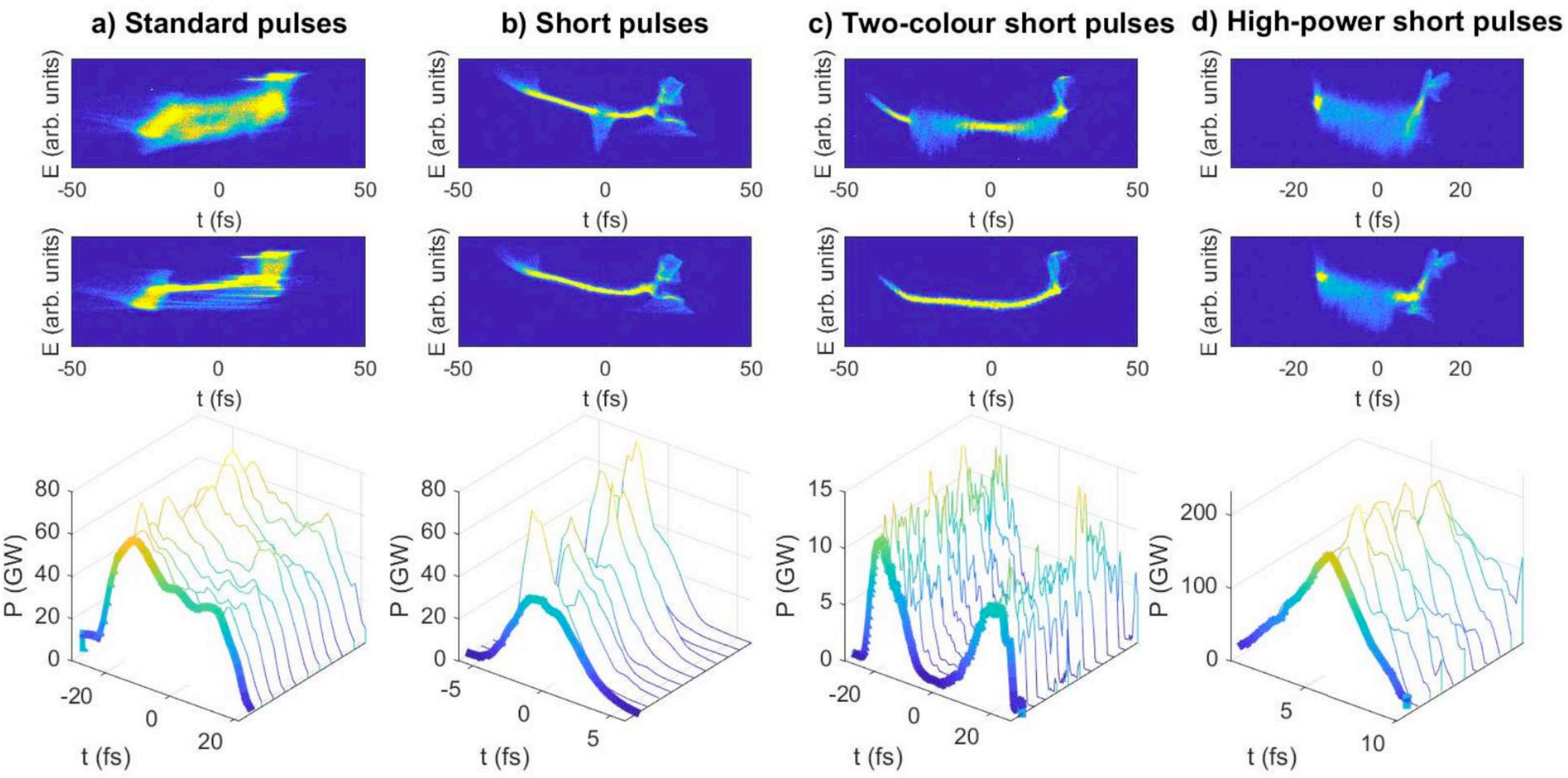
Bunch centroid on a BPM after TDSs as a function of the RF phase. Polarization variation of 5 deg.





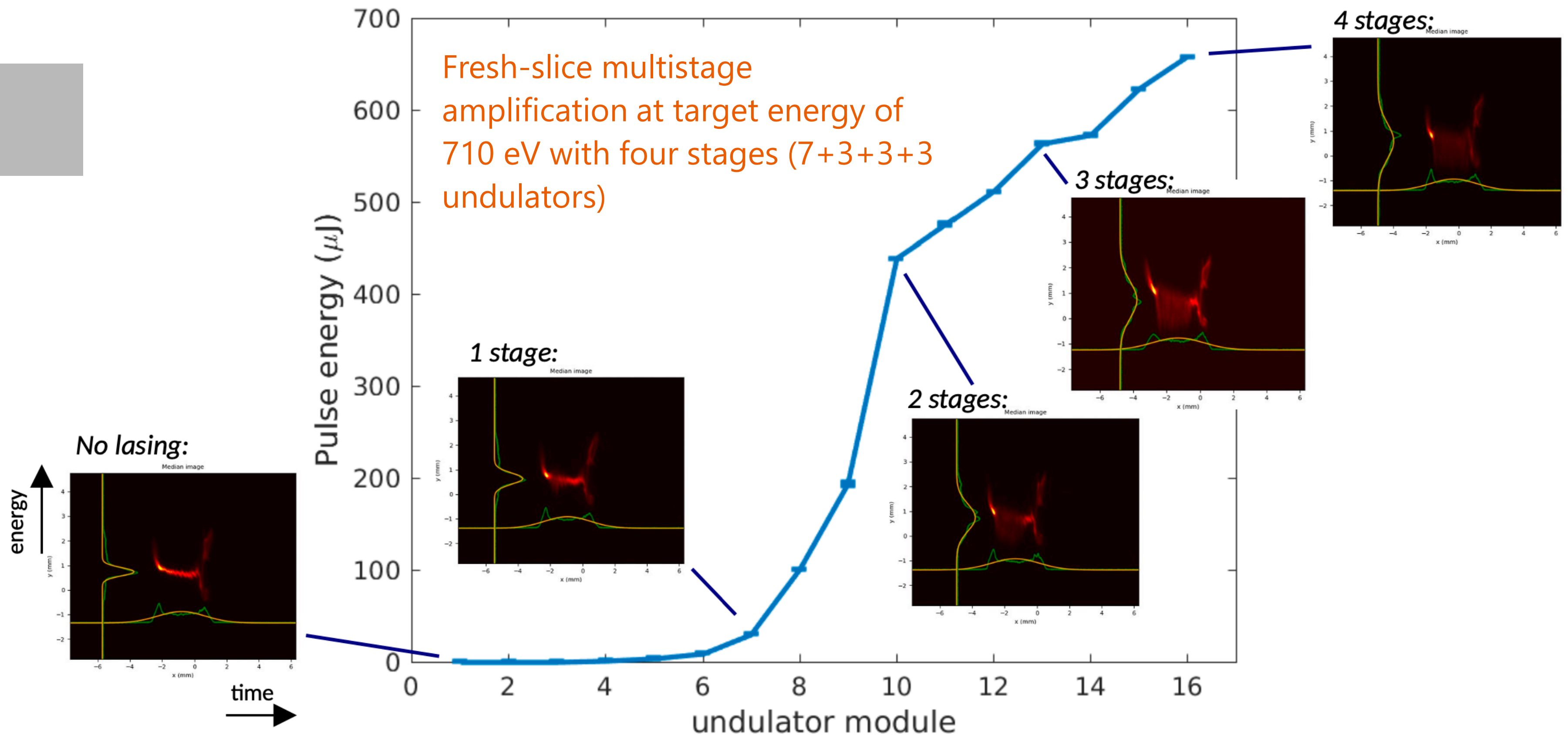
Right plots: Images on screen before dipole as a function of polarization angle. Dark polarization angles: 85 MW, red polarization angles: 72.8 MV.

Setup of the FEL modes (beam dump screen)



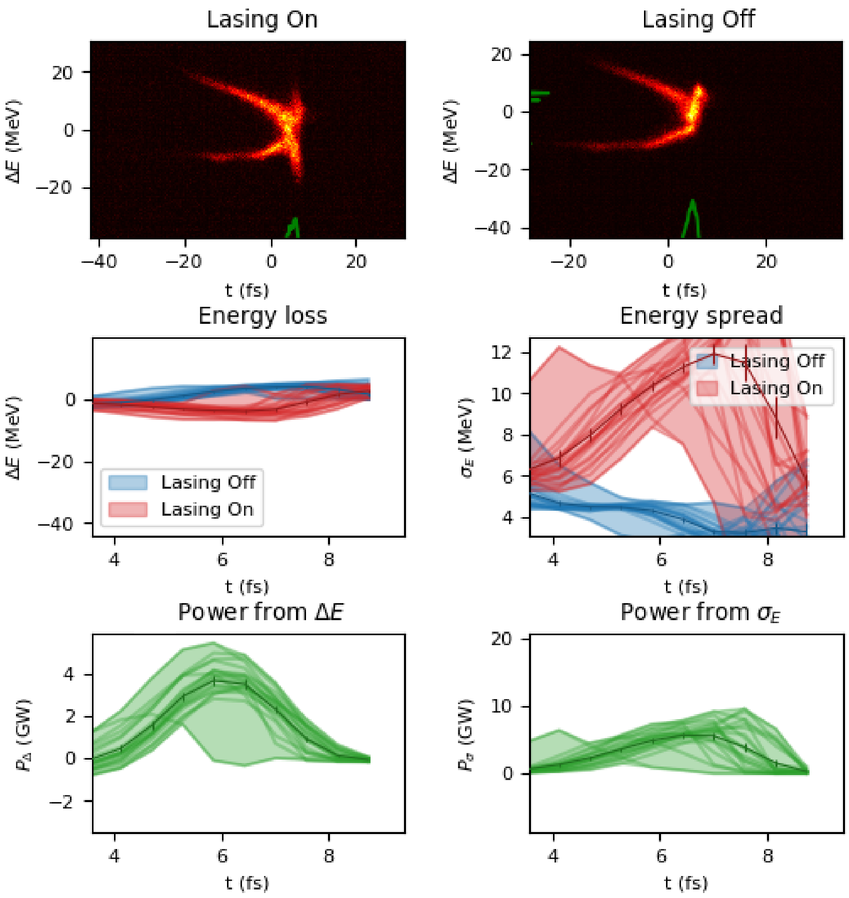
E. Prat et al., Nature Communications v. 14, 5069 (2023)

Example of Athos setup (beam dump screen)

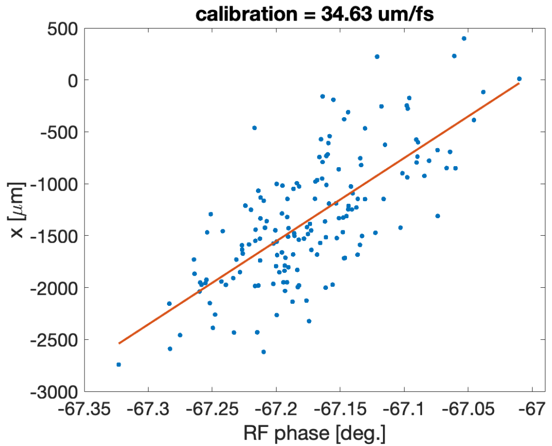


E. Prat, G. Wang,
T. Weilbach, Ch. Kittel

Short pulse mode (10 pC) – and higher jitter



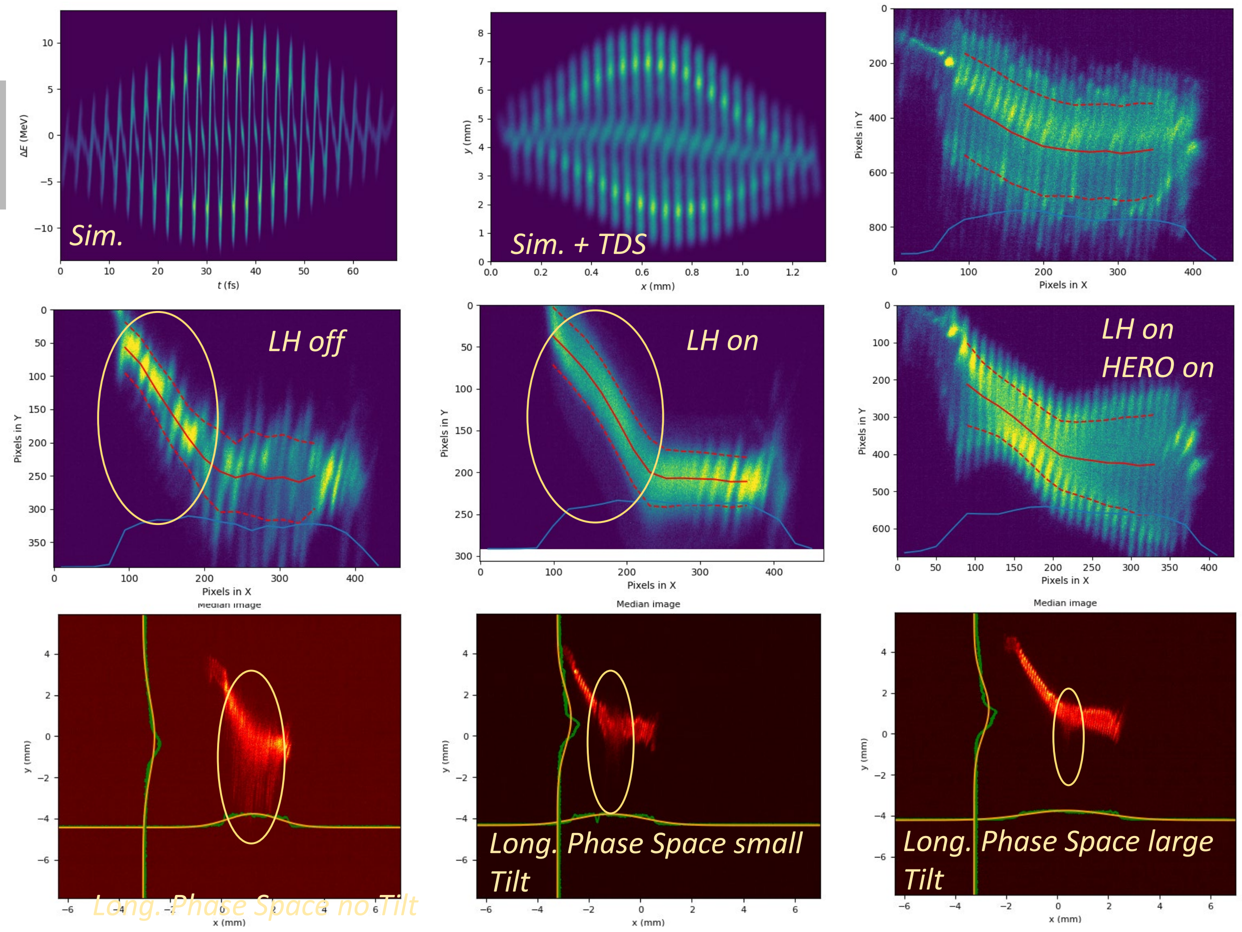
Plots by E. Prat



For some modes of operation, a jitter on the images was observed at the screen, which made the calibration of the TDS system difficult

- In order to perform the time calibration and bunch length measurement in the presence of jitter, we may exploit the jitter itself.
- the calibration coefficient can be estimated with reasonable accuracy by means of a linear regression between the values of the beam centroid at the screen and the RF phase jitter values.

Seeding at SwissFEL



ESASE: the periodicity of the modulation is 800 nm, corresponding to 2.66 fs. It shows that we have a resolution well be 1 fs

Effect of the laser Heater used to damp microbunching instability in ESASE

Controlling the Pulse Length with Tilts

Courtesy of S. Reiche

Outlook

- PolariX TDS: Try pushing the time resolution below 0.5 fs (in different streaking plane) – higher power, lower jitter, larger screen…
- Study on the overall streaking efficiency with rf pulse compressor (F. Marcellini, talk at HG2023, INFN LNF, 16-20 Oct 2023)
- Repetition rate up to 10 Hz, future operation up to 100 Hz (provide shot-to-shot photon pulse length to users) - mainly by improving phase jitter
- Slide emittance measurements in different deflecting planes
- Implement the measurement for a full 5-dimensional phase space reconstruction
- Systematic comparison between the passive (streaker) and active (TDS system) streaking

Conclusion

- TDS-based diagnostics systems are essential tools for the commissioning and optimization of linac-based FELs (**temporal resolution below 1 fs with C-band and X-band RF systems**)
- Streaking with a RF deflecting structure reveals the full longitudinal phase space, slice emittance and can also provide information on the 5D phase space
- Placed down stream of the undulator also reveals lasing temporal profile in the FEL
- They are also key devices for diagnosing the beam in new acceleration techniques (before and after acceleration). Here the sub-fs resolution is even more important!
- But, expensive and subject to phase jitter
  - Ideally, the power source should be phase-locked to the beam (as in the passive streakers)

Credits

- To prepare my slides, I have especially used material from: E. Prat, F. Marcellini, S. Reiche
- Thanks to my colleagues at PSI involved in the design, development and commissioning of the TDS systems
- Thanks also go to our colleagues at CERN and DESY involved in this collaboration for the useful discussions. Especially S. Jaster-Merz (DESY) for the slides related to activities at DESY
- And thank to P. Krejcik (SLAC) and E. Mansten (MAX IV) for useful discussion on their TDS systems
- Some more details for the PolariX TDS:

The PolariX TDS Project: a novel Polarizable X-Band Transverse Deflection Structure

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Deutsches Elektronen-Synchrotron, 22607 Hamburg, Germany
(Dated: June 28, 2020)

https://doi.org/10.1103/PhysRevAccelBeams.23.112001

scientific reports

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OPEN **Experimental demonstration of novel beam characterization using a polarizable X-band transverse deflection structure**

B. Marchetti[1,4], A. Grudiev[2], P. Craievich[3], R. Assmann[1], H.-H. Braun[3], N. Catalan Lasheras[2], F. Christie[1], R. D'Arcy[1], R. Fortunati[3], R. Ganter[3], P. González Caminal[1], M. Hoffmann[1], M. Huening[1], S. M. Jaster-Merz[1], R. Jonas[1], F. Marcellini[3], D. Marx[1,5], G. McMonagle[2], J. Osterhoff[1], M. Pedrozzi[3], E. Prat Costa[3], S. Reiche[3], M. Reukauff[1], S. Schreiber[1], G. Tews[1], M. Vogt[1], S. Wesch[1] & W. Wuensch[2]

https://doi.org/10.1038/s41598-021-82687-2

P. Craievich, Z. Geng, F. Marcellini, C. Kittel, S. Reiche, T. Schietinger, G. Wang, E. Prat, "Post-undulator beam measurements with PolariX TDS in SwissFEL," Proc. SPIE 12581, X-Ray Free-Electron Lasers: Advances in Source Development and Instrumentation VI, 1258106 (9 June 2023); doi: 10.1117/12.2665447

SPIE. Event: SPIE Optics + Optoelectronics, 2023, Prague, Czech Republic

https://doi.org/10.1117/12.2665447

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Home — Session — Classification — Authors
Institutes — DOI of Institutes — Keywords

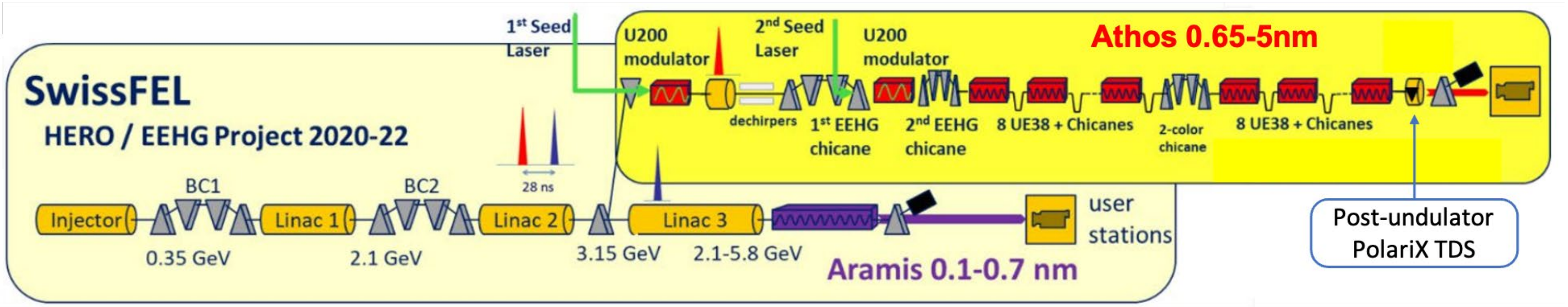
Sonja Jaster-Merz

WEODB2	5D phase-space reconstruction of an electron beam	4

The complete knowledge of electron bunch properties is of great interest to understand and optimize the performance of accelerators and their applications. A new tomographic beam diagnostics method to reconstruct the full 5-dimensional phase space (x, x', y, y', t) of bunches has recently been proposed. This method combines a quadrupole-based transverse phase-space tomography with the variable streaking angle of a polarizable X-band transverse deflection structure (PolariX TDS). In this contribution, we show preliminary data of the first experimental demonstration of the method including the reconstruction of the full 5-dimensional phase space distribution of an electron bunch at FLASHForward.

- **S. Jaster-Merz**
  Deutsches Elektronen-Synchrotron

ATHOS: the Soft X-rays beamline in SwissFEL



Relevant hardware:

- 8x2 undulator APPLE-X modules: variable field, variable polarization, Transverse-Gradient Undulator (TGU)
- Inter-undulator Chicanes for High power and Improved Coherence (CHIC): R56 + delay
- 2-color chicane
- 2 x (laser + modulator + chicane)
- Temporal diagnostics :
  - Post-undulator X-Band RF system (PolariX-TDS)
  - Post-undulator passive streaker

– For SASE process:

- Reduction of the saturation length, variable polarization, higher peak power and shorter pulse durations with increasing longitudinal coherence and bandwidth: High-Brightness SASE (HB SASE), large bandwidth. Fresh-slice multi-stage amplification
- Widely tunable two-color pulses

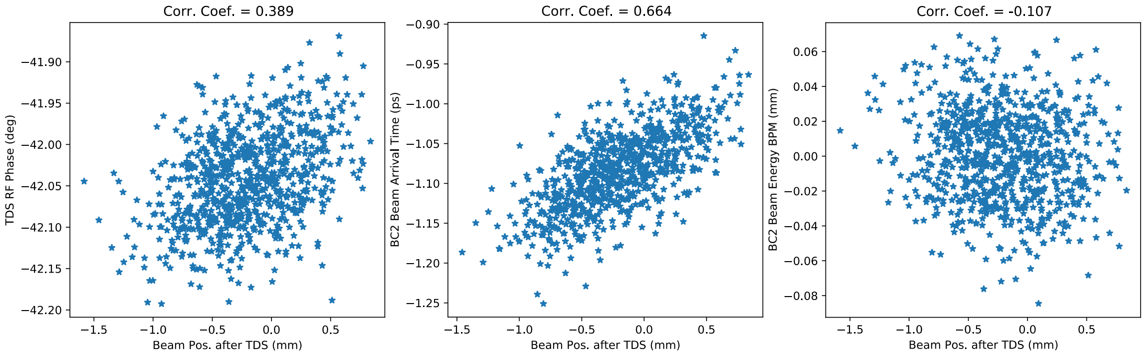
– With optical lasers for external seeding:

- Production of trains of attosecond pulses with the Enhanced SASE (ESASE) mechanism
- Phase-locked pulses
- Echo-Enabled Harmonic Generation (EEHG)

PAUL SCHERRER INSTITUT

RF setup and commissioning with beam

RF Phase and beam arrival time jitter can be limiting factors in achieving higher resolution



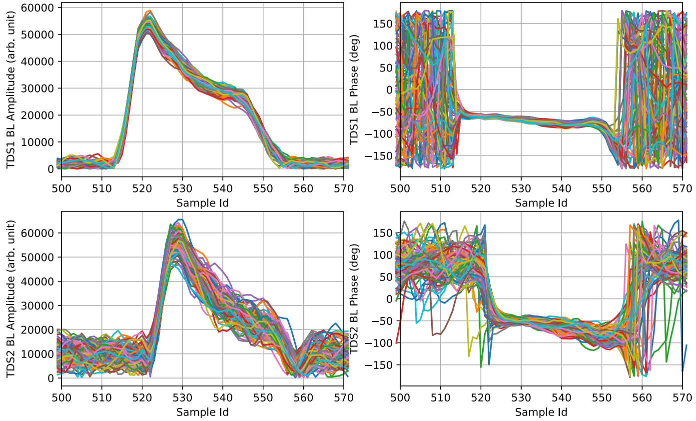
Correlations between streaked beam centroid measured on the BPMs after the TDSs and RF phase (left), beam arrival time (middle) and mean energy (right) in BC2

Calibrated time jitter on the screen ~10 fs

Beam loading amplitude and phase

TDS 1

TDS 2



The beam-loading phase of TDS2 fluctuates more than twice in magnitude compared to TDS1 → this could be caused by an initial angle when the beam enters in TDS2 (due to an angle in the beam orbit itself), or by transverse wakefield effects in TDS1.

Use a proper signal (beam loading) to be used for RF feedbacks could improve the RF phase jitter

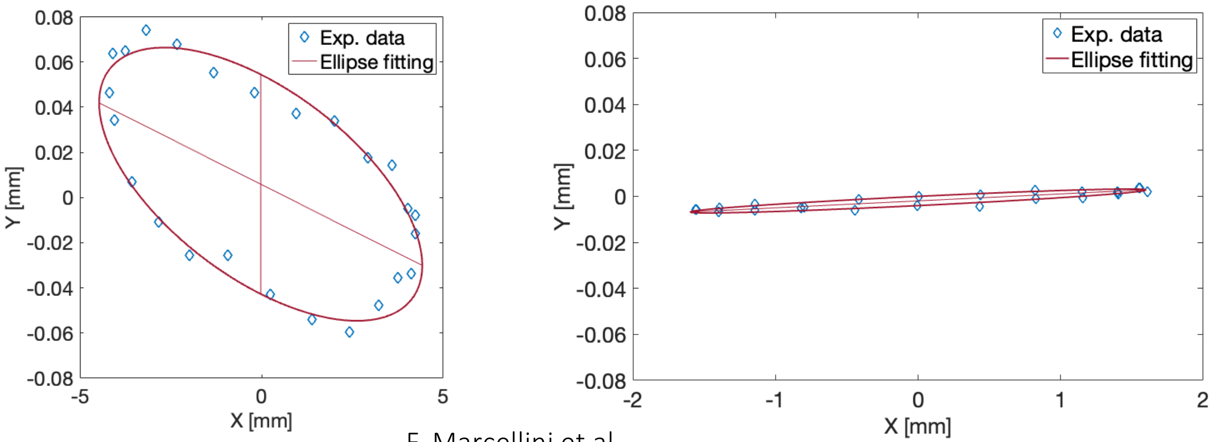
Plots by Z. Geng

RF setup and commissioning with beam

$$\vec{V}_+ = L\cos(\varphi_{\mathrm{RF}} + \varphi_L + \varphi_{\mathrm{PS}})\hat{x} + L\sin(\varphi_{\mathrm{RF}} + \varphi_L + \varphi_{\mathrm{PS}})\hat{y},$$
$$\vec{V}_- = R\cos(\varphi_{\mathrm{RF}} + \varphi_R)\hat{x} - R\sin(\varphi_{\mathrm{RF}} + \varphi_R)\hat{y}$$

Deflecting field is the sum of two rotating modes, one clockwise and the other counter clockwise

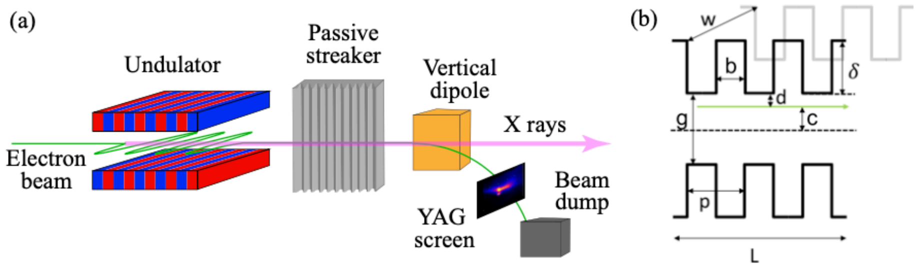
Wrong setting of the PSs and/or the amplitudes are unbalanced then the superposition of the two rotating modes results in an elliptically polarized mode, whose effect is to provide a kick in the plane orthogonal to the streaking plane (we will call this effect a *residual kick*).

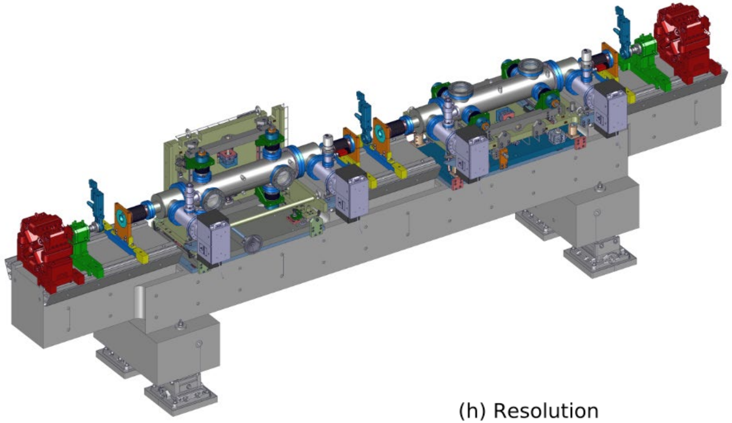


F. Marcellini et al.

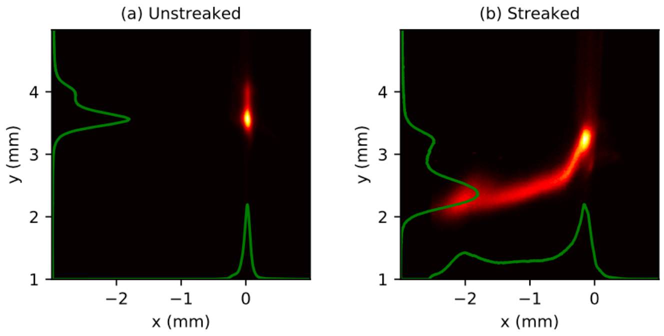
Post-undulator passive streaking (Aramis)

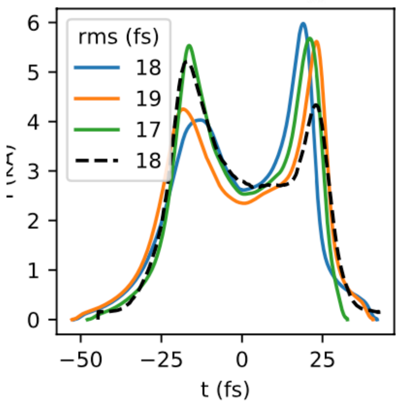
more information: P. Dijkstal et al., *PRR 2, 042018(R), 2020*)

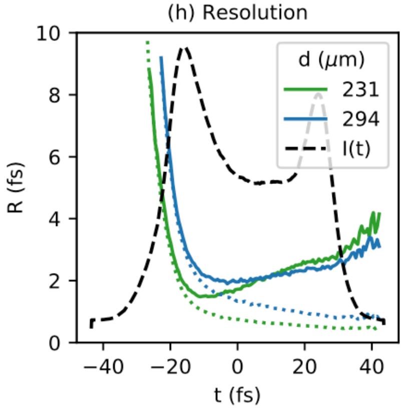




An electron beam traveling off-axis through such a device excites transverse wakefields, resulting in a time-dependent kick that streaks the electron beam.

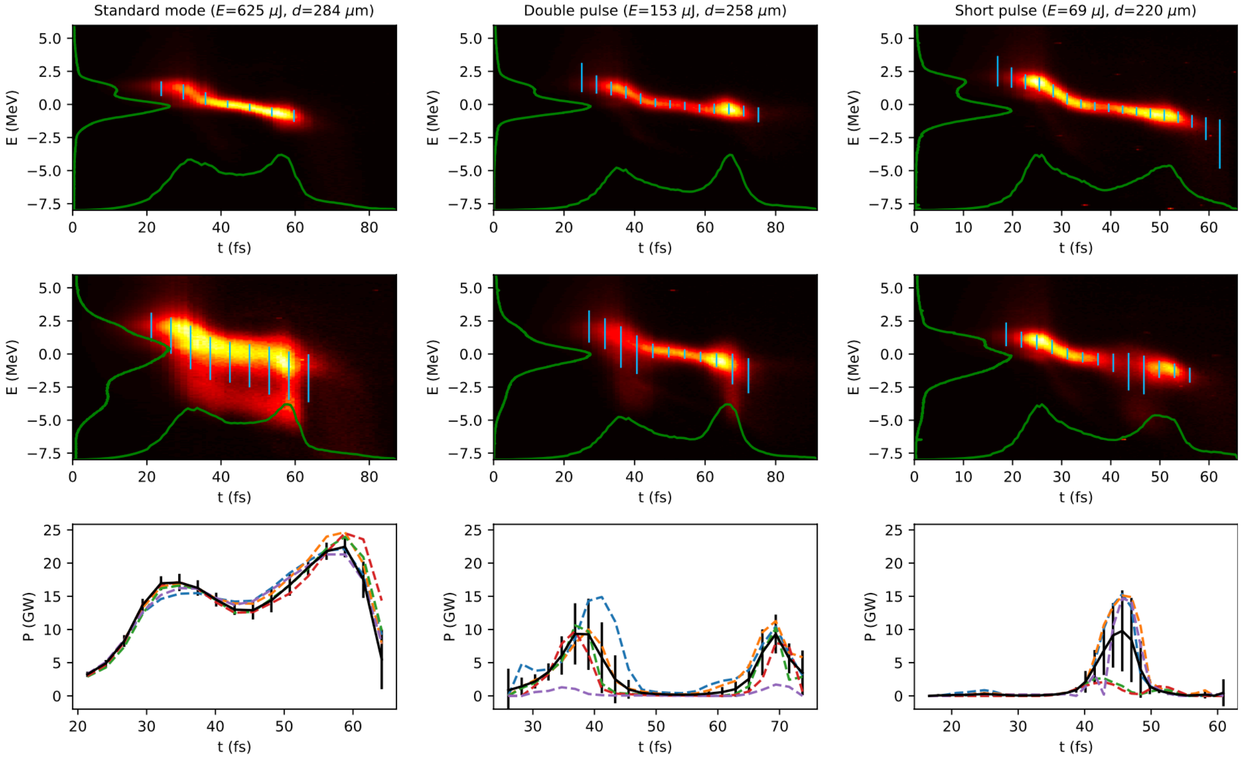






Post-undulator passive streaking – LPS

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



Passive wakefield deflectors can have similar resolution

- Not limited in rep. rate, not subject to jitter, relatively inexpensive

- But, nonlinear response only kicks the tail of the bunch

- Also useful for two-bunch, two-color pump probe experiments

Diagnostics of variable lasing modes at SwissFEL