The New LOLA/TDS Setup and Results on TDS-induced Energy Spread.

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Deutsches Elektronen-Synchrotron (DESY)

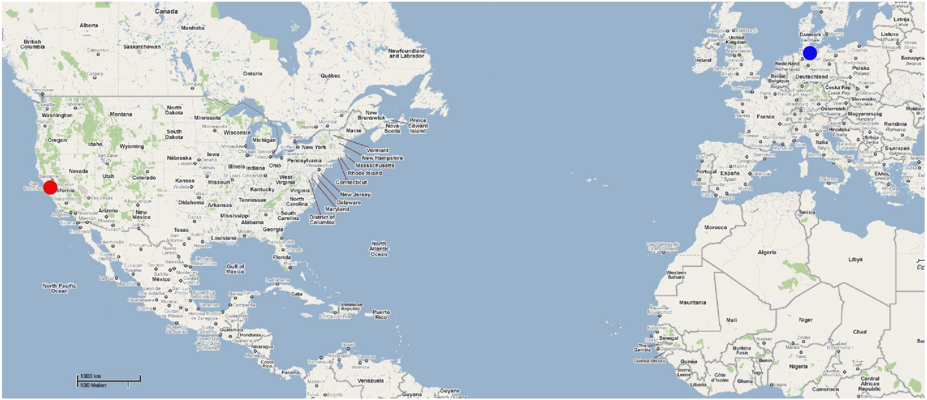
FLASH Seminar: June 6th, 2011

Outline

1. The Transverse Deflecting RF-Structure (TDS) “LOLA” at FLASH in the Past
2. The FLASH Upgrade in 2009/2010
3. Longitudinal Beam Diagnostics Using a Transverse Deflecting Structure
4. The New LOLA/TDS Setup
   - Design Considerations and Expected Performance
   - Experimental Setup and Achieved Performance
   - Some Highlights and Problems
5. Results on LOLA/TDS-induced Energy Spread

The Transverse Deflecting RF-Structure (TDS) “LOLA” at FLASH

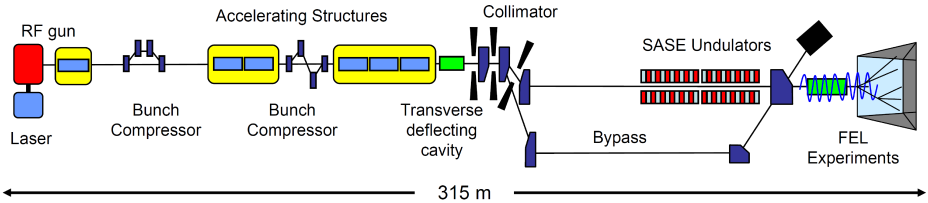
A Short History of the Transverse Deflecting RF-Structure “LOLA”.

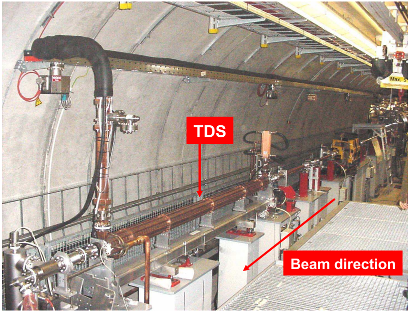


Transverse Deflecting RF-Structure (TDS) “LOLA”

- 1960’s: Originally designed at SLAC for particle separation by RF fields .
- 2003: Transported to FLASH (formerly TTF2) for longitudinal beam diagnostics.
- 2010: New position with a dedicated sliced-beam-parameter setup.

FLASH and the LOLA/TDS Setup Before Shutdown.





Drawbacks of the Old Position

- Measurements not directly in front of the undulators.
- No dedicated setup for longitudinal phase space measurements.
- Lattice prevented good longitudinal resolution during FEL operation.

Example Measurements (M. Röhrs *et al.*) : FEL Operation.

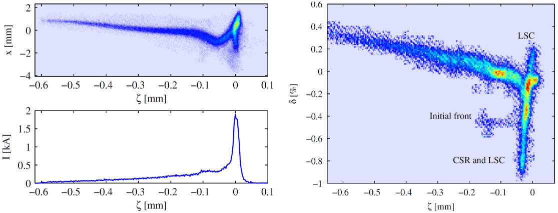


Figure: Left: Bunch current, Right: Longitudinal phase space.

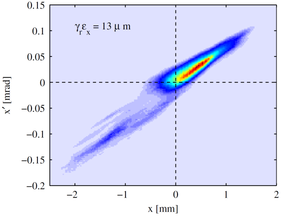


Figure: Horizontal phase space (projected).

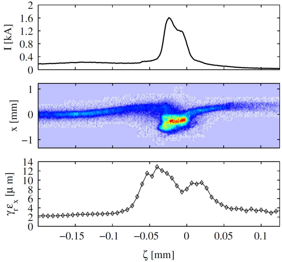
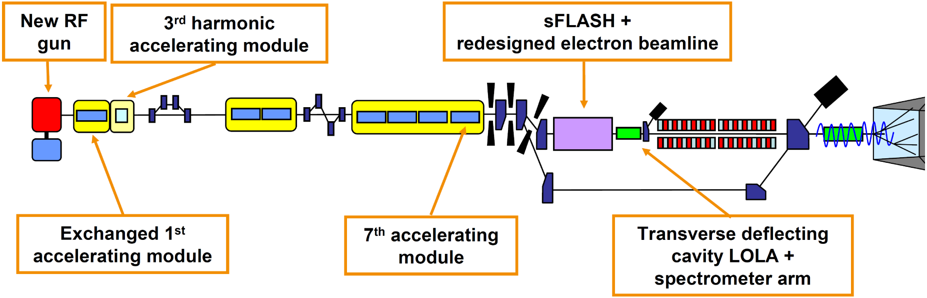


Figure: Slice emittance.

The FLASH Upgrade in 2009/2010

Shutdown Activities: Sept. 2009 - Feb. 2010.



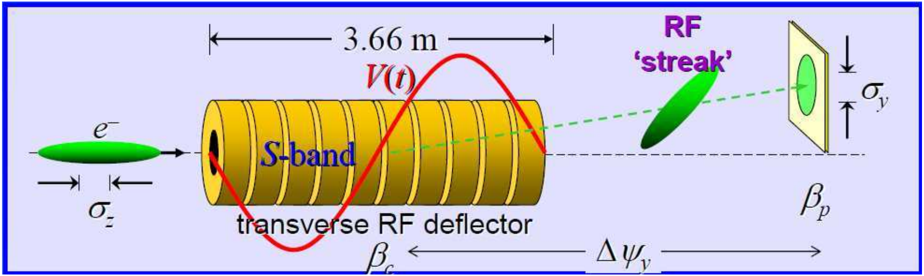
- Third-harmonic RF cavity for longitudinal phase space linearizations.
- New Sliced-Beam-Parameter measurement setup directly in front of the undulators.

Special Requirements on the New LOLA/TDS Setup

- Parasitic measurements during FEL operation.
- Dipole spectrometer for longitudinal phase space investigations.
- Both with much improved resolution.

Longitudinal Beam Diagnostics Using a Transverse Deflecting Structure

Operation Principle.



- TDS translates longitudinal coordinate into transverse coordinate. (Vertical: y)
- Shear parameter S determines the strength of this translation.

In combination with a dispersive section (dipole spectrometer) $\Rightarrow$ "Longitudinal Phase Space"

- Dipole spectrometer translates energy into transverse coordinate. (Horizontal: x)
- Dispersion D determines the strength of this translation.

Resolution and Bunch Parameters.

Longitudinal Resolution σ_ζ

- $\boxed{\sigma_\zeta = \frac{\sigma_{y_\beta}(s)}{S(s)}} = \sqrt{\epsilon_y} \cdot pc \cdot \frac{1}{\sqrt{\beta(s_0)} \cdot \sin(\Delta\Phi_y)} \cdot \frac{1}{eV_0 k}$ $\Leftarrow$ important for lattice design
- Example: $\sigma_{y_\beta} = 100\,\mu\text{m}$ and $S = 10$: $\Rightarrow \sigma_\zeta = 10\,\mu\text{m}\ (30\,\text{fs})$.

Relative Energy Resolution σ_δ

- $\boxed{\sigma_\delta = \frac{\sigma_{x_\beta}(s)}{D_x(s)}} = \sqrt{\epsilon_x} \cdot \frac{\sqrt{\beta_x(s)}}{D_x(s)}$ $\Leftarrow$ important for lattice design
- Example: $\sigma_{x_\beta} = 100\,\mu\text{m}$ and $D_x = 1000\,\text{mm}$: $\Rightarrow \sigma_\delta = 1 \cdot 10^{-4}$.

Obtainable Bunch Parameters

- Bunch current and length.
- Longitudinal emittance.
- Energy spread (slice and projected).
- Transverse emittance (slice and projected).

The New LOLA/TDS Setup

Design Considerations and Expected Performance

Lattice Design and Theoretical Resolutions.

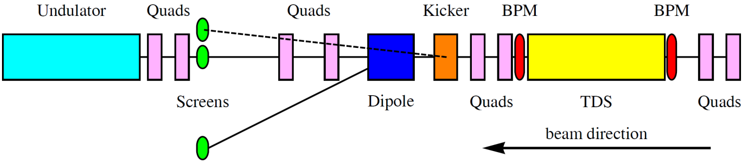


Figure: Generic layout as template.

Special requirements on the setup.

General Requirements

- Flexible lattice in order to match into the undulators (different energies and focusing options).
- Standard diagnostics like beam position/charge monitors and beam imaging systems.
- Steering magnets for sufficient obit corrections.

Theoretical Resolutions

- Longitudinal resolution: below $6\,\mu\text{m}$ $(20\,\text{fs})$.
- Relative energy resolution: $1 \cdot 10^{-4}$ ($D \lessapprox 1000\,\text{mm}$).

Limitations on Resolutions.

Longitudinal Resolution

- Beam optics and RF power.

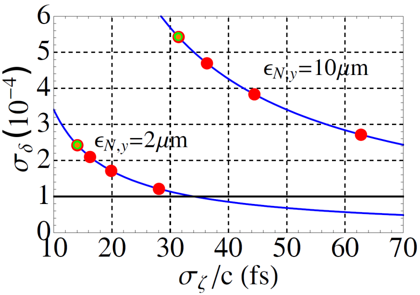
Energy Resolution

- CSR effects in the spectrometer ⇒ minor impact.
- The TDS itself ⇒ can be a large effect.

The TDS induces energy spread due to longitudinal electric fields. (Panofsky-Wenzel Theorem)

Relations (found in 2009)

- Induced energy spread: $\sigma_\delta = \frac{eV_0 k}{pc} \cdot \sigma_y$
- Induced energy spread is inversely proportional to the longitudinal resolution.
- Analytical results: checked by simulations using `elegant`.



Simulations on the Diagnostics Performance.

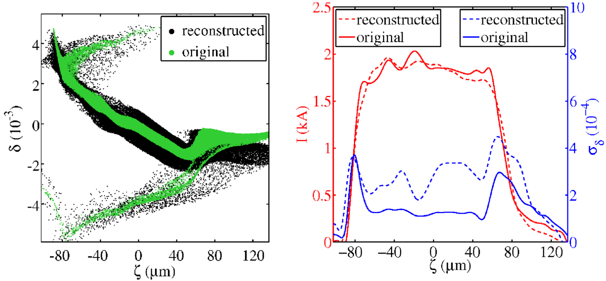


Figure: Simulated Measurement: Longitudinal phase space (left), Bunch current and energy spread (right).

Simulated Measurements

- Same procedure as in reality.
- Transverse beam profiles.
- Calibrations: S and D

Particle Tracking

- Up to the TDS (I. Zagorodnov): ASTRA and `CSRtrack`.
- TDS to the screen: `elegant`.

- Energy spread: In agreement if the TDS-induced energy spread is taken into account.
- Longitudinal beam profile: In good agreement.

The New LOLA/TDS Setup

Experimental Setup and Achieved Performance

Beamline/Lattice Design.

The last 13 m in front of the undulators have been redesigned and rebuilt.

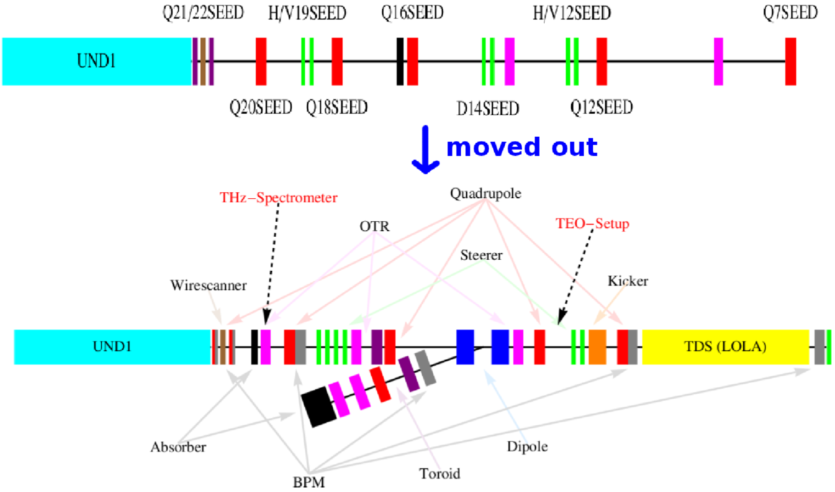


Figure: Transition from old to new beamline/lattice.

Beamline/Lattice Design.

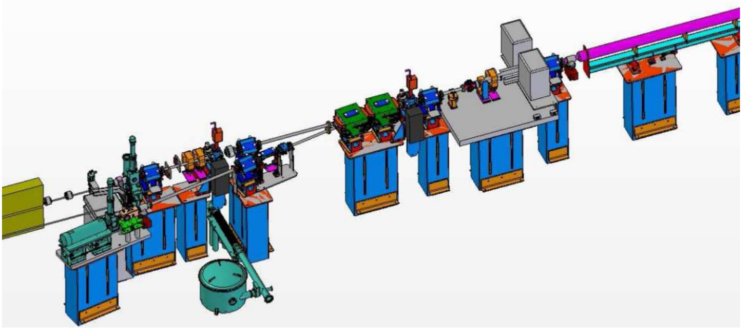


Figure: Latest design installed in February 2010.

Fulfilment of all Boundary Conditions Including:

- Space for dedicated experiments like TEO or the THz-spectrometer.
- Space for vacuum stuff and the stretched wire system.

Everything is tightly packed and space was the main issue during the design!

Final Layout.

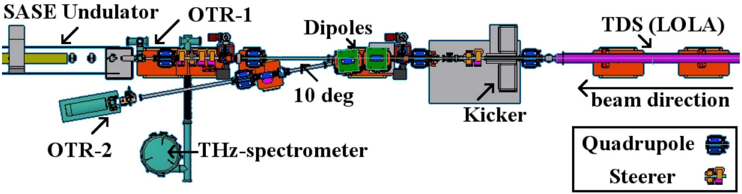


Figure: Latest design installed in February 2010.

Beamline Nomenclature

- Straight Section with OTR-1: SMATCH
- Dispersive Section with OTR-2: SDUMP

Imaging Stations OTR-1/2

- Equipped with OTR and scintillator screens.
- Use new fully motorized camera systems.
- OTR-1 can be used for THz-spectroscopy.

Imaging Screens and Performance.

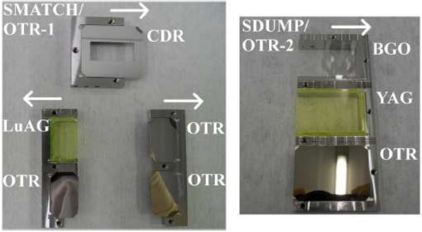
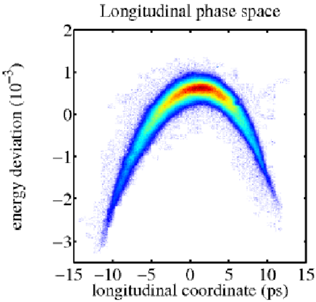
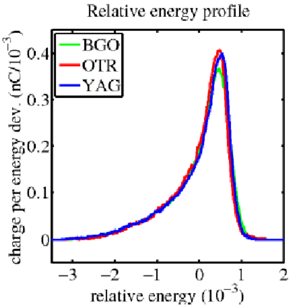


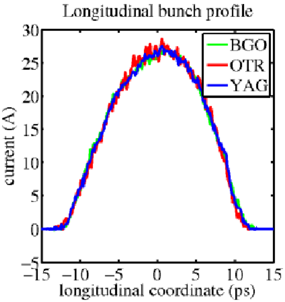
Table 1: Properties of the observation screens.

Screen material	Thickness (mm)
YAG:Ce ($Y_3Al_5O_{12}$:Ce)	0.1
LuAG:Ce ($Lu_3Al_5O_{12}$:Ce)	0.1
BGO ($Bi_4Ge_3O_{12}$)	0.1
OTR (Al coated silicon)	0.380 (150 nm Al)
CDR (Al coated silicon with cutout)	0.380 (150 nm Al)

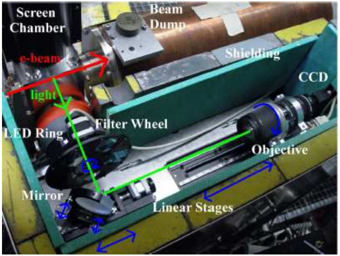
Figure: Different screens and materials (OTR and scintillatros).







Camera System and Resolution.



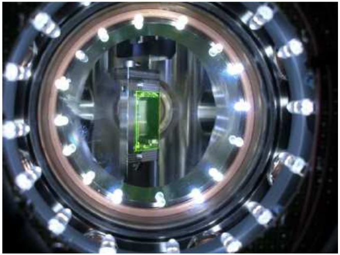


Figure: Left: Camera System in SDUMP, Right: OTR-1 with LuAG screen and LED-Ring.

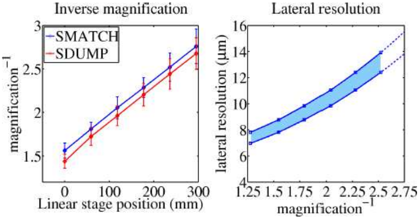


Figure: Magnification and lateral resolution.

CCD-Camera and Macro Lens

- Prosilica GC1380 (12 bit).
- Pixel size is 6.45 μm x 6.45 μm
- 1024 x 1360 pixels
- Macro Lens: 180mm, Teleconverter: x 1.4
- Camera distance and focusing is variable.

Time and Energy Resolution.

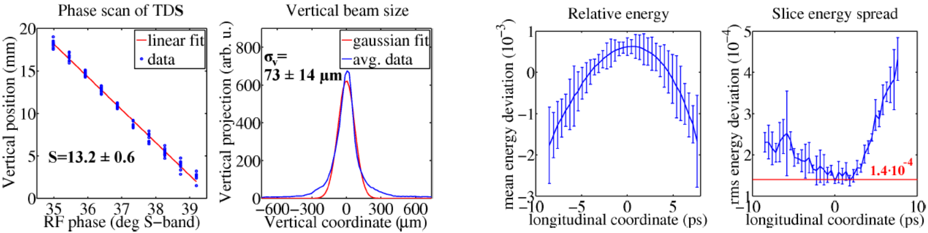


Figure: Estimation of Resolution. Left: Time Resolution. Right: Energy Resolution.

Conservative Estimation of Resolution

- Time: See beginning of this talk ($\sigma_{y,0}/S$).
- Energy: Minimum slice energy spread of uncompressed bunches.

Achieved Resolutions (already during commissioning in 2010)

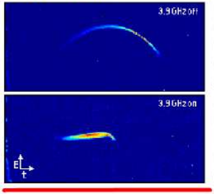
- Time: 18$\pm$3 fs at 1200 MeV.
- Rel. Energy: 1.4$\cdot 10^{-4}$(100 keV) at 700 MeV $\Rightarrow$ less than 0.9$\cdot 10^{-4}$ at 1200 MeV.
- Both like expected (slightly better) and in parallel to FEL operation, i.e. no special optics.

The New LOLA/TDS Setup

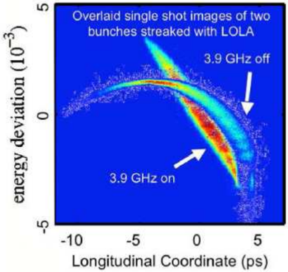
Some Highlights and Problems

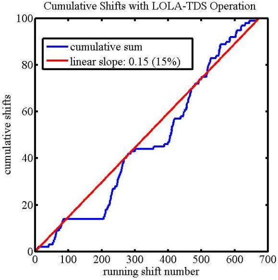
Functionality of the Third-harmonic RF System and LOLA Statistics.

FLASH flach - Das 3,9 GHz-Modul optimiert den FLASH-Teilchenstrahl



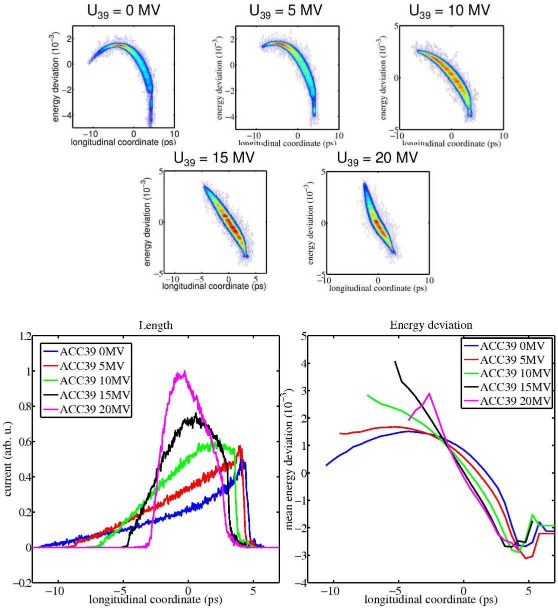
Eine der Schlüsselkomponenten der neuen Ausbaustufe des FLASH-Beschleunigers hat seine Funktion unter Beweis gestellt. Das neu integrierte 3,9-GHz-Modul konnte in Testläufen die Energieverteilung in den beschleunigten Elektronenpaketen reduzieren – unter Fachleuten Linearisierung des Phasenraums genannt. Diese Optimierung erzeugt ultrakurze Teilchenpakete mit einer hohen Stromstärke, aber auch Pakete mit gleichbleibender Intensität und regelbarer Länge. So wird eine erhebliche Leistungssteigerung von FLASH erreicht. » mehr





- The functionality of the third-harmonic RF System was demonstrated.
- The new LOLA setup was in operation from “day 1”, i.e. before any beam arrived.
- LOLA was used by many other people (than me) in 15% of all 8h shift periods in 2010.

Longitudinal Phase Space Linearization.



Shortest Bunches.

21.01.2011 09:29 Short Bunches et al. tp21a11a4d_c56b_4eec_9f4e_0bdd6b839c

```
Even after switching BC3 off during the night and 8hours in between without FEL operation, we have
 almost the same long. phase space as in the night shift and also with good lasing. The
 machine and the beam dynamics is really reproducible except for slow drifts.
The bunch lengths are below 40fs rms.

Cheers
Christopher

This elogbook entry was sent to following experts:
Limberg Schreiber
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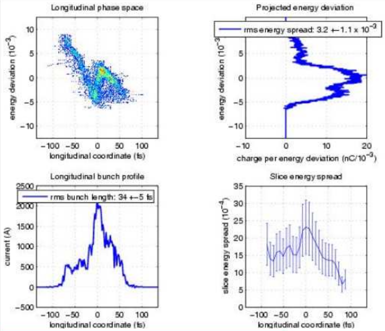

Bunches with lengths well below 50 fs (34 fs rms) and regular shapes have been measured.

Highest Resolutions.

21.01.2011 09:24 ttflinac **Record of time resolution, 7fs!**

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This resolution was achieved for the 34fs bunches above.

Cheers
Chris

This elogbook entry was sent to following experts:
Honkavaara Schreiber Vogt
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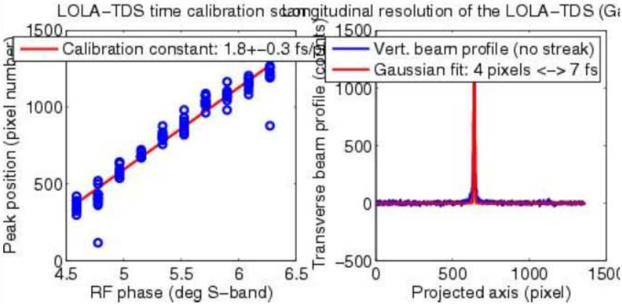
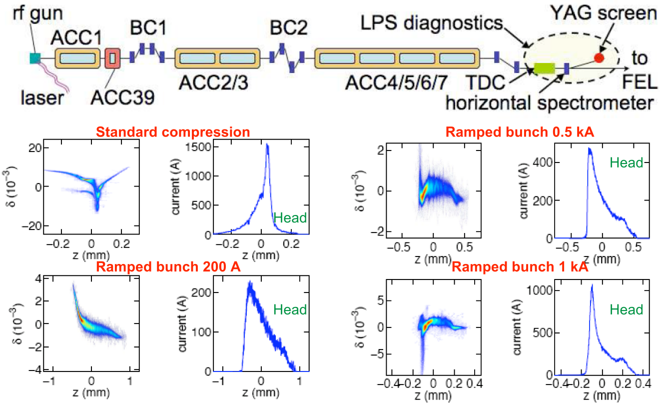


The time resolutions was pushed below 10 fs (7 fs rms) which is world record.

Tailoring of the Longitudinal Phase Space (initiated by P. Piot).

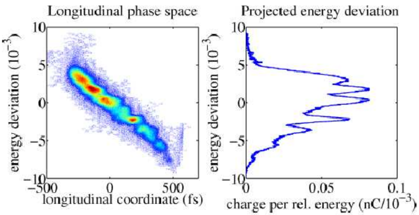
Control of LPS distortions: demonstration at FLASH@DESY

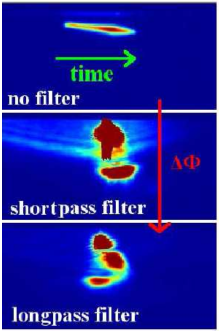


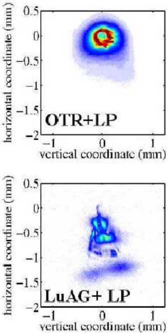
Measured LPS for different settings of ACC39 [Piot, Behrens, Gerth, 2011][5]

"Linearly"-ramped current profiles have been produced ⇒ interesting for wakefield accelerators.

Microbunching Instability and COTR.







Hints for COTR in SDUMP

- Modulations in the longitudinal phase space.
- Characteristic for linear compression mode.

COTR Observation in SMATCH

- First operation of screens in SMATCH.
- Slightly changed phases during FEL operation.
- Filters and minimizing gain do not help.
- Even scintillators (“stand-alone”) are useless!

RF Phase Scan of ACC1 in 0.05 deg Steps: 7.75 deg.

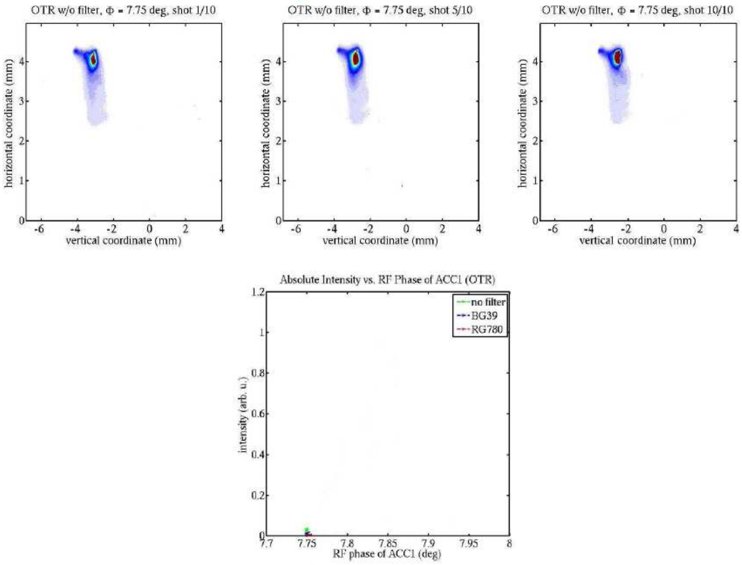


Figure: OTR profile and integrated intensity.

RF Phase Scan of ACC1 in 0.05 deg Steps: 7.80 deg.

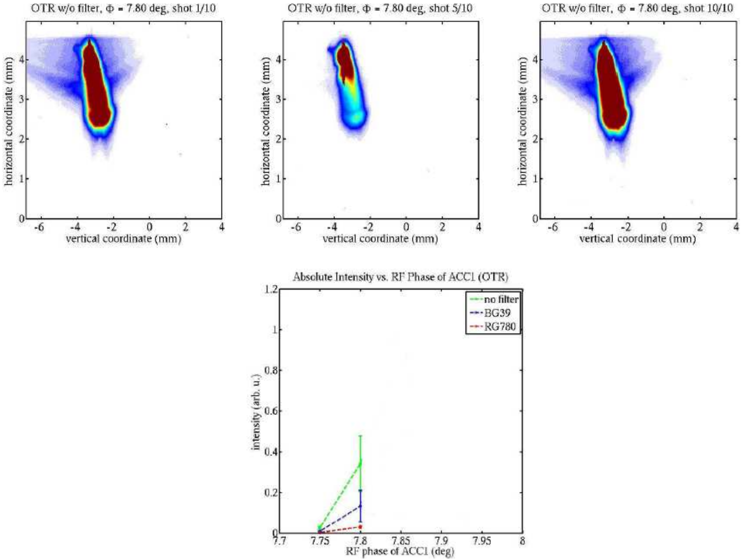


Figure: OTR profile and integrated intensity.

RF Phase Scan of ACC1 in 0.05 deg Steps: 7.85 deg.

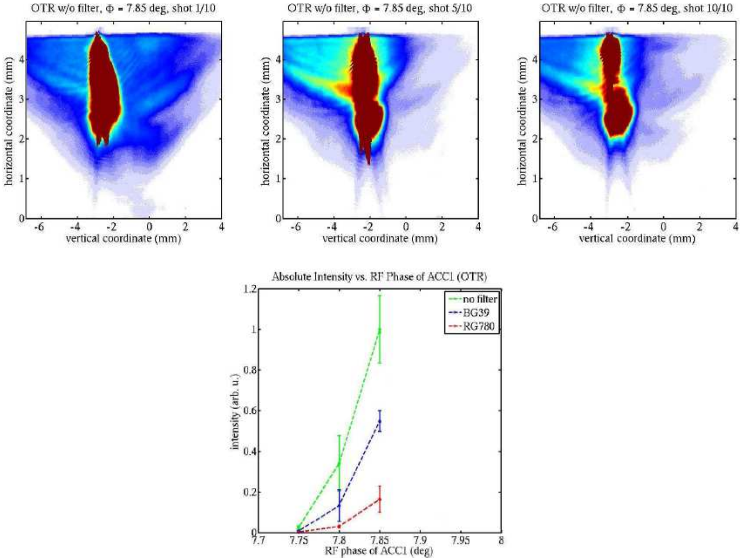


Figure: OTR profile and integrated intensity.

RF Phase Scan of ACC1 in 0.05 deg Steps: 7.90 deg.

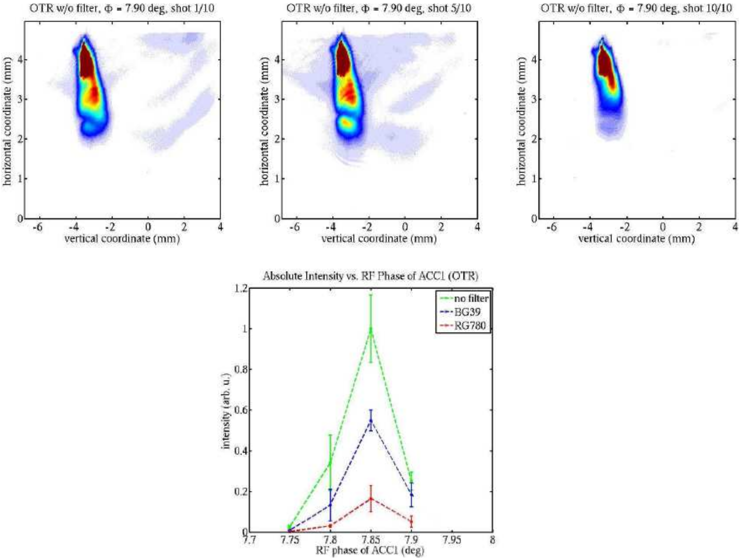


Figure: OTR profile and integrated intensity.

RF Phase Scan of ACC1 in 0.05 deg Steps: 7.95 deg.

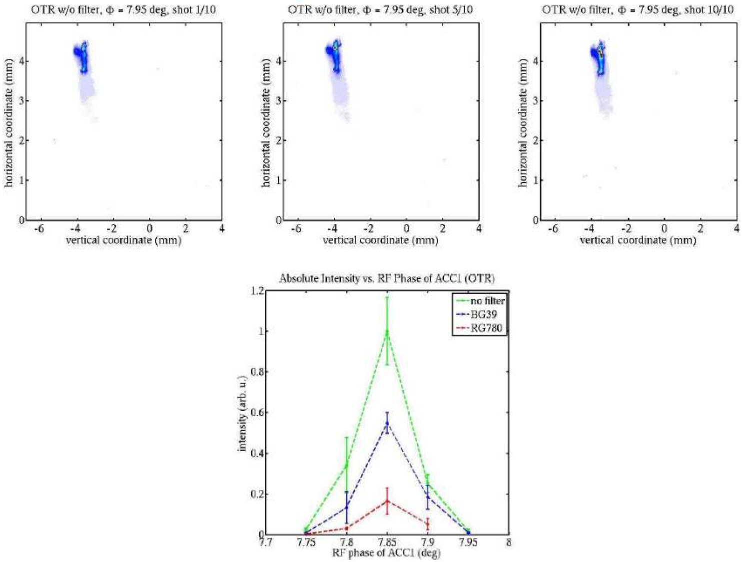
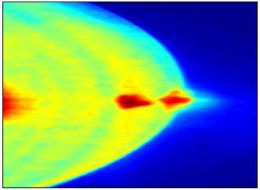


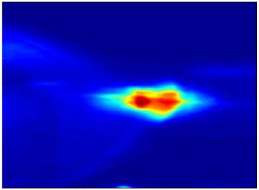
Figure: OTR profile and integrated intensity.

Possible Solution Investigated by Minjie Yan.

Utilizing a scintillation screen with a fast gated CCD camera.

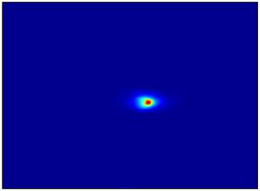


(a) OTR screen



(c) LuAG screen

(b) OTR screen, +100ns delay



(d) LuAG screen, +100ns delay

Figure 3: Camera images of the beam with (a) OTR screen, (b) OTR screen with 100 ns camera delay, (c) LuAG screen, (d) LuAG screen with 100 ns camera delay.

Results on LOLA/TDS-induced Energy Spread

TDS-induced Energy Spread: Theory.

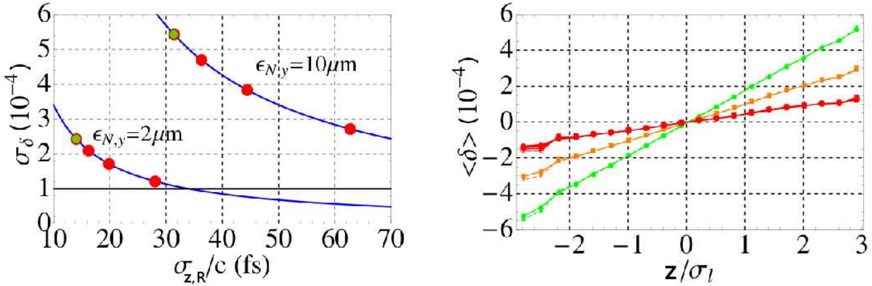


Figure 2: Left: Induced energy spread as a function of the longitudinal resolution. Dots indicate the results of simulations with the code `elegant`; blue lines represent the expression in Eq. (16). Right: Mean energy spread along the bunch for the cases in the left plot with the same colour coding. V_0: 20 MV (red), 30 MV (orange), and 40 MV (green).

$$\delta = \frac{eV_0 k}{pc} \cdot \frac{1}{L} \int_0^L y(s) \cdot ds \,, \qquad (1)$$

$$T = \begin{pmatrix} 1 & L & KL/2 & 0 \\ 0 & 1 & K & 0 \\ 0 & 0 & 1 & 0 \\ K & KL/2 & K^2L/6 & 1 \end{pmatrix} \,, \quad (y, y', z, \delta)^{\mathrm{T}} \qquad (3)$$

$$\sigma_\delta = \frac{eV_0 k}{pc} \cdot \sigma_y = K \cdot \sigma_y \,, \qquad (2)$$

$$\frac{d}{dz}\delta = \frac{1}{6} K^2 L \,. \qquad (4)$$

TDS-induced Energy Spread: Beam Preparation.

$$\sigma_\delta = \frac{\epsilon_y}{\sin(\Delta\Phi_y)} \cdot \sigma_{z,R}^{-1}, \quad \text{and} \tag{5}$$

$$\frac{d}{dz}\delta = \frac{1}{6}\frac{\epsilon_y}{\sin^2(\Delta\Phi_y)}\frac{L}{\beta_0} \cdot \sigma_{z,R}^{-2} \tag{6}$$

Equations (5) and (6) are used to check the effect of TDS-induced energy spread.

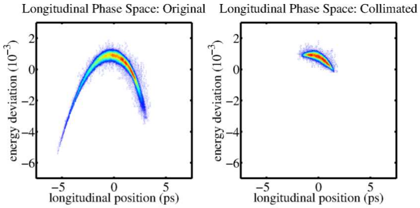


Figure 1: Bunch tailoring for verification of TDS-induced energy spread and linear chirp. Left: Measured longitudinal phase space for on-crest acceleration. Right: Same accelerator settings as in left plot but with low energy electrons clipped with a movable collimator in the first bunch compressor.

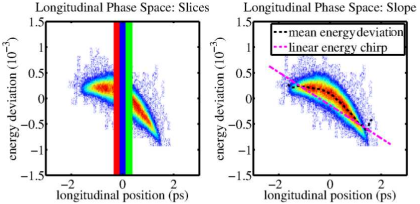


Figure 2: Data evaluation procedure for verification of the TDS-induced energy spread and linear chirp. Left: Three slices (colored) around the centroid with slice widths equal to the resolution. Right: Linear energy chirp between the mean energy at longitudinal positions of $\pm 1.5\sigma_z$.

TDS-induced Energy Spread: Results I.

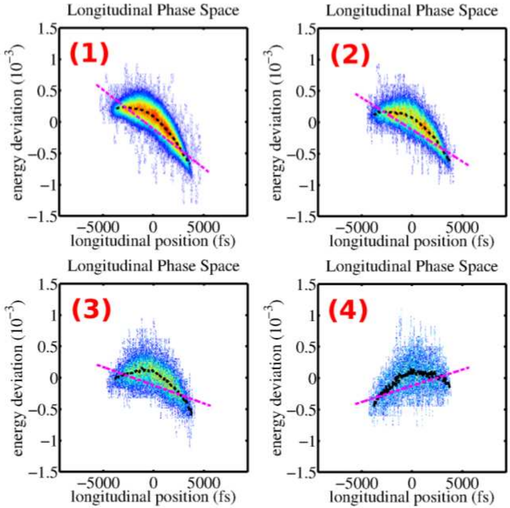


Figure 3: Longitudinal phase space measurements for different deflecting voltages V_0 of the TDS. The achieved longitudinal resolution increases from plot (1) to (4).

TDS-induced Energy Spread: Results II.

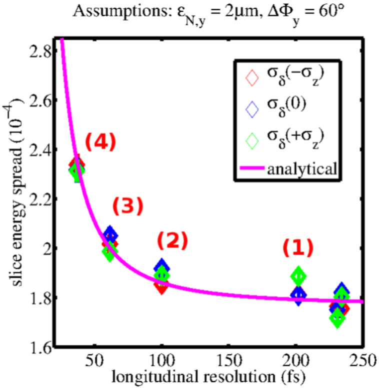


Figure 4: Measured slice energy spread (colored diamonds) for the three different slices around the centroid as function of longitudinal resolution together with the result of the analytical expression (magenta line) in Eq. (5).

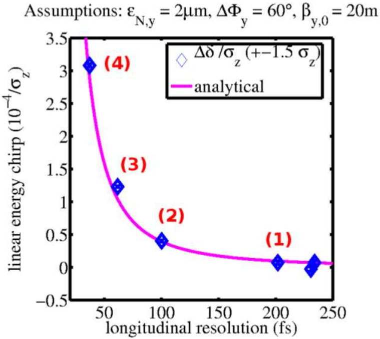


Figure 5: Measured linear energy chirp (symbols) induced be the TDS as function of the longitudinal resolution together with the result of the analytical expression (magenta line) in Eq. (6).

The effect is clearly visible and with some reasonable assumptions, the measurements are in good agreement with the analytical expressions.

Thanks for your attention!