Paolo Craievich :: Paul Scherrer Institut

The PolariX TDS
A novel X-band Transverse Deflection Structure (TDS) with variable polarization
(collaboration between CERN, DESY and PSI)

ICFDT5 - 5th International Conference on Frontier in Diagnostic Technologies
INFN-LNF, 3-5 October 2018

Outline

- Motivation for high-resolution time-resolved diagnostic
- TDS as a diagnostic tools
  - State of the Art of X-band TDS systems
  - Next generation TDS
- CERN-PSI-DESY Collaboration
  - Status and plan
- PolariX -TDS Applications
  - SwissFEL – ATHOS at PSI
  - FLASH2, FLASHForward, SINBAD at DESY

Motivation for high-resolution time-resolved diagnostics

Ongoing Tendency of Getting Shorter and shorter Electron Bunches

- **FEL science (user):** novel imaging techniques in X-ray FELs require shorter (sub-fs/as) FEL X-ray pulses
  - Single-shot characterization of the longitudinal phase space of the beam allows for single-shot reconstruction of the X-rays pulses
- **Novel high-gradient acceleration technique:** Laser Wakefield Plasma Acceleration – LWFA, Beam Driven Plasma Acceleration –PWFA, THz driven Acceleration, Dielectric Laser Driven Acceleration - DLA) are characterized by short period of accelerating field and therefore naturally produce or accelerate fs long beams
  - Longitudinal characterization of the driver and witness electron beams is essential for characterizing and optimizing the acceleration channel

How to measure ultra-short bunches and pulses…

- with fs or sub-fs resolution?, with single shot capability?, fully parasitically?
- parallel to fs electron beam diagnostics (useful information like energy chirp etc.)?

… a possible solution

RF Transverse Deflection Structure (TDS) in combination with an energy (dipole) spectrometer

→ Single-shot capability and high resolution in both energy and time

Experiments joining the PolariX TDS project

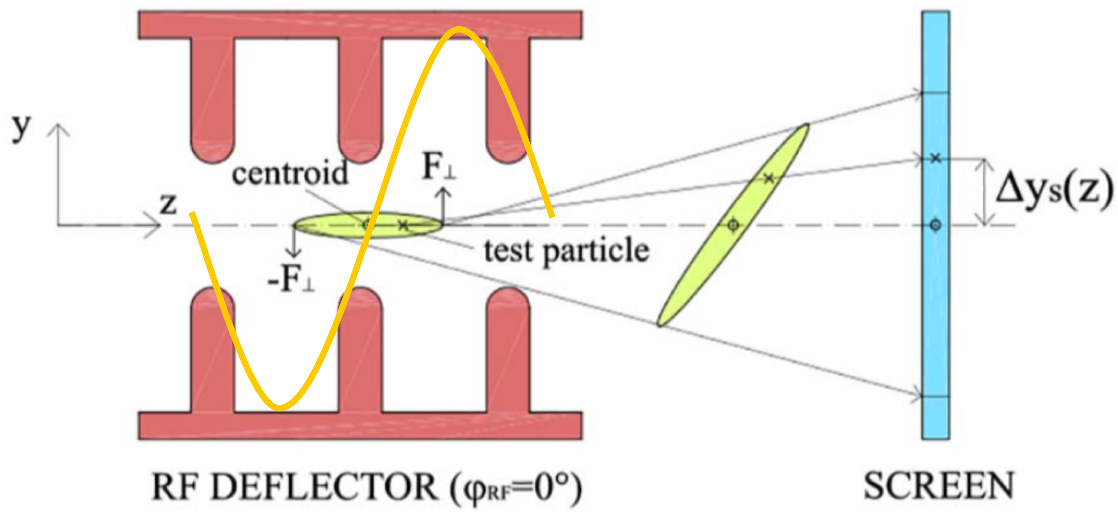
At PSI

- ❑ **ATHOS** at SwissFEL
  → Soft X-rays FEL

At DESY

- ❑ **FLASHForward**
  → PWFA experiment
- ❑ **FLASH2**
  → FEL single spike at ~30 nm wavelength
- ❑ **SINBAD**
  → LWFA, DLA, THz driven acceleration etc.
- ❑ **Potentially XFEL**

TDS as a diagnostic tool – working principle



TDS imposes a time-dependent transversal kick Δy'(z) ~ sin(kz) ≈ kz (at zero-crossing)

$$\Delta y_S(z) \approx \frac{eV_\perp}{pc} R_{34} \left(k_{rf} z \cos\varphi_{rf} + \sin\varphi_{rf} \right)$$

The calibration factor at the screen is defined as the ratio between the beam size at the screen and the temporal bunch length:

$$S = \frac{\sigma_y}{\sigma_t} = \frac{eV_\perp}{pc} c k_{rf} \sqrt{\beta_d \beta_s} \sin(\Delta\psi_{ds})$$

TDS as a diagnostic tool – resolution

Longitudinal resolution is limited by the vertical beam size and the calibration factor S:

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

Electron bunch:

- beam energy
- normalized emittance $\varepsilon_{N,y}$

Optics:

- phase advance
- beta function at TDS

RF structure:

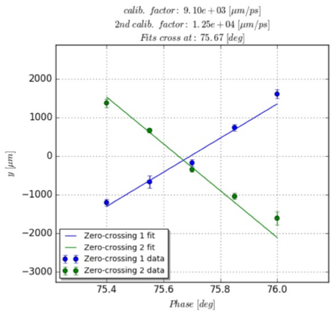
- wave number $k_{rf} = \omega_{rf}/c$
- Deflecting voltage $V_\perp$

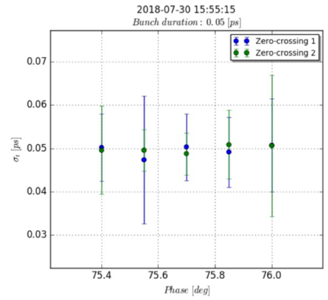
✓ **~12 GHz (X-band) frequency allows having 4 times higher resolution than ~3 GHz (S-band) frequency**

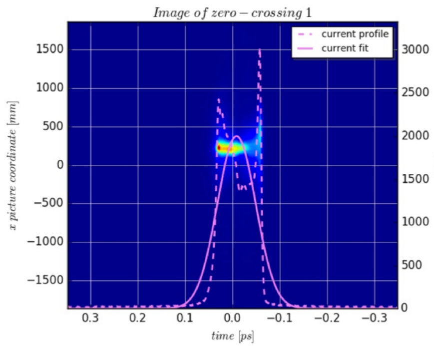
✓ **Shorter structure with large kick**

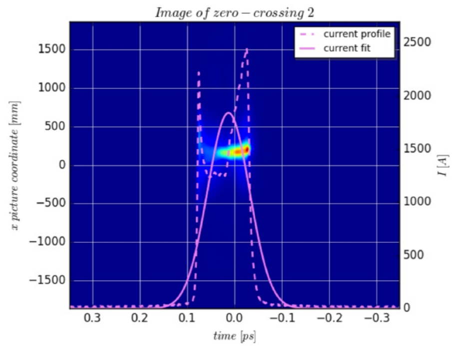
TDS as a diagnostic tool – capabilities

- ❑ **Bunch length** measurement
- ❑ **Longitudinal charge profile** measurement

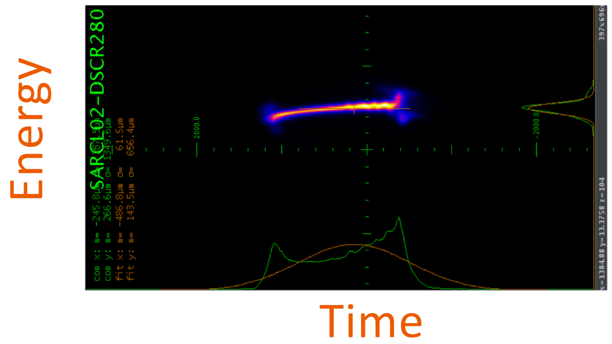


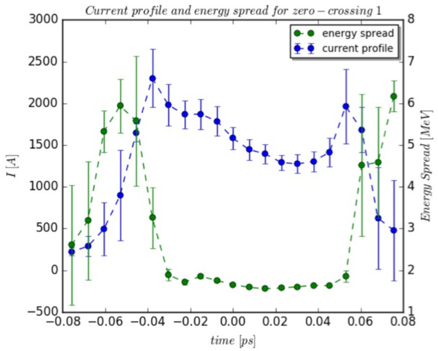




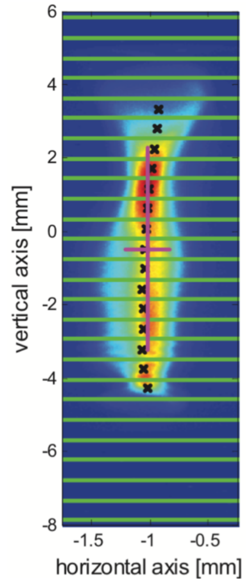


- ❑ Combined with dipole → **longitudinal phase space** measurement

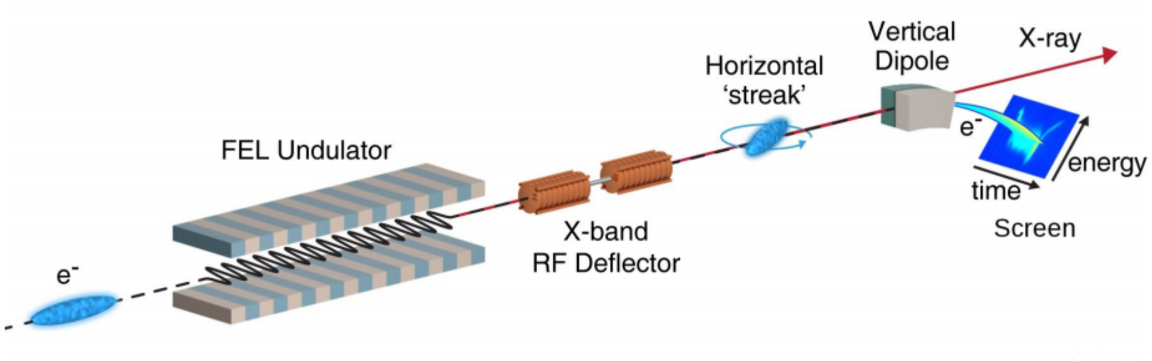




- ❑ Combined with quadrupole scan or multi-screen lattice → **slice emittance** measurement <u>on the plane perpendicular to the streaking direction</u>, **slice transverse phase space** reconstruction
- ❑ <u>**Method capable of fs and sub-fs longitudinal resolution**</u>



State of the Art of X-band TDS systems



X-band transverse cavity very valuable instrument to:

- ❑ Measurement of the energy spread induced by the FEL process at SLAC
- ❑ Optimize the lasing along the bunch

Behrens et al., Nature Communications, DOI: 10.1038/ncomms4762.

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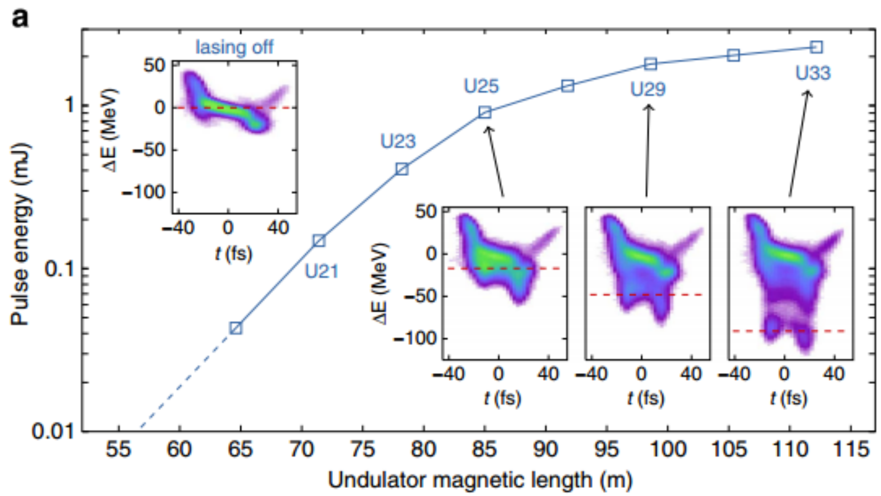
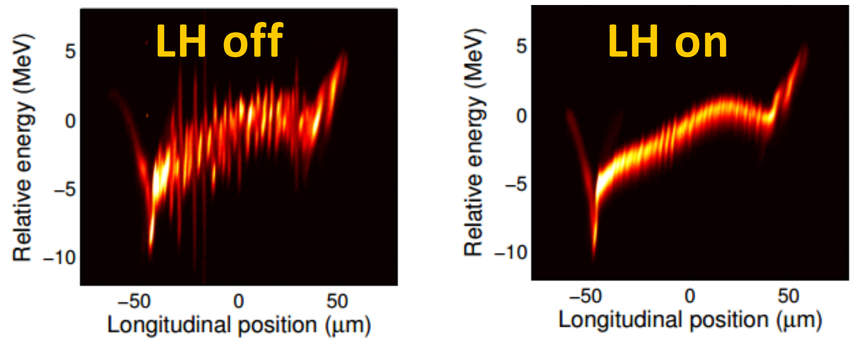
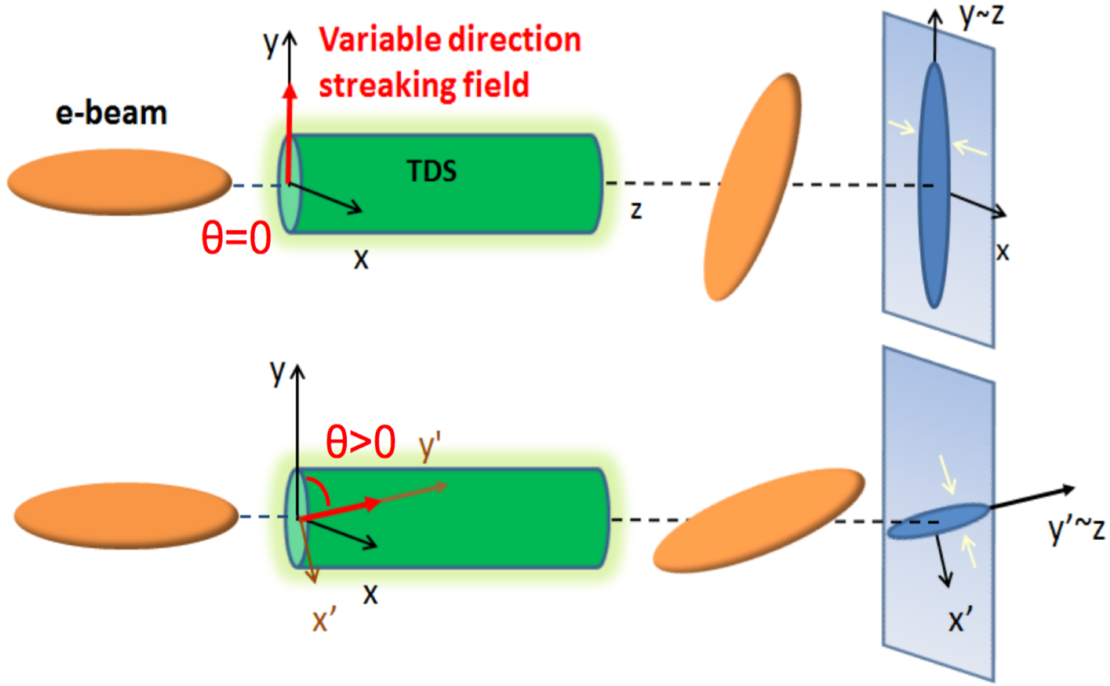


- ❑ Directly observe the microbunching instability and its mitigation



D. Ratner et al., PRST AB 18, 030704 (2015).

Next generation TDS



Relies on **streaking at multiple angles**

New opportunities for e-bunch characterization

→ i.e. slice emittance measurement on different planes

3D charge density distribution reconstruction

→ identify correlations, tilts of the beam distribution in 3D

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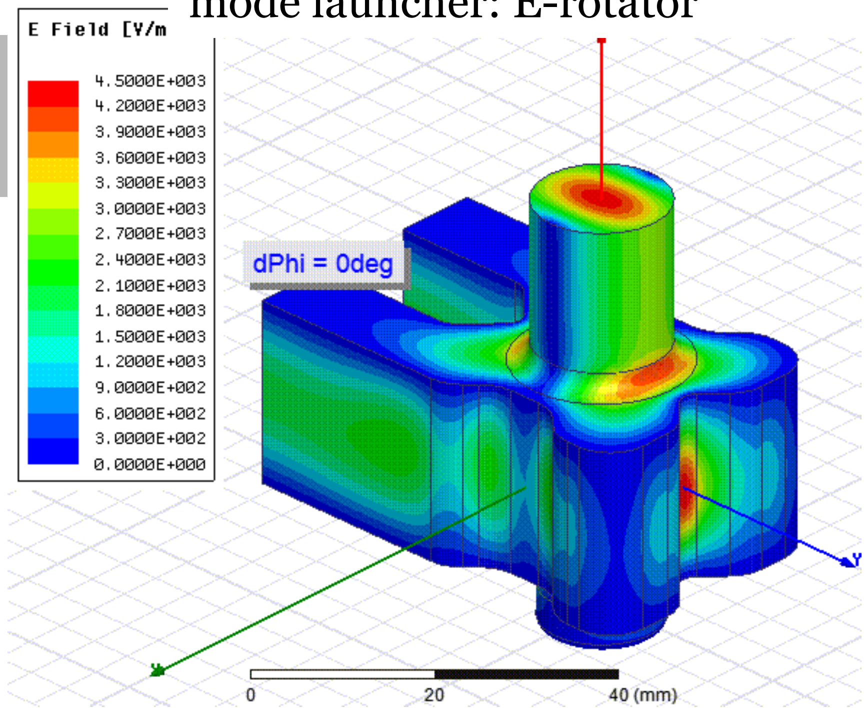
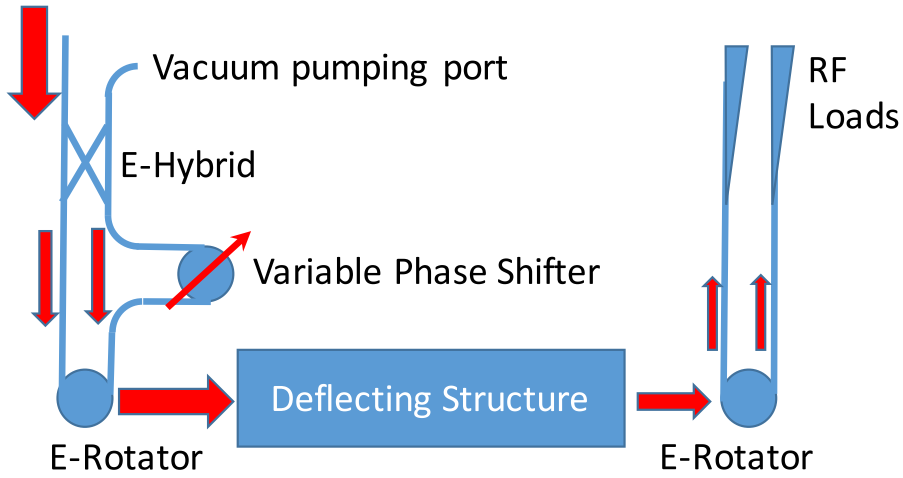
PolariX TDS: Novel Concept with Variable Polarization

Variable polarization circular TE11 mode launcher: E-rotator

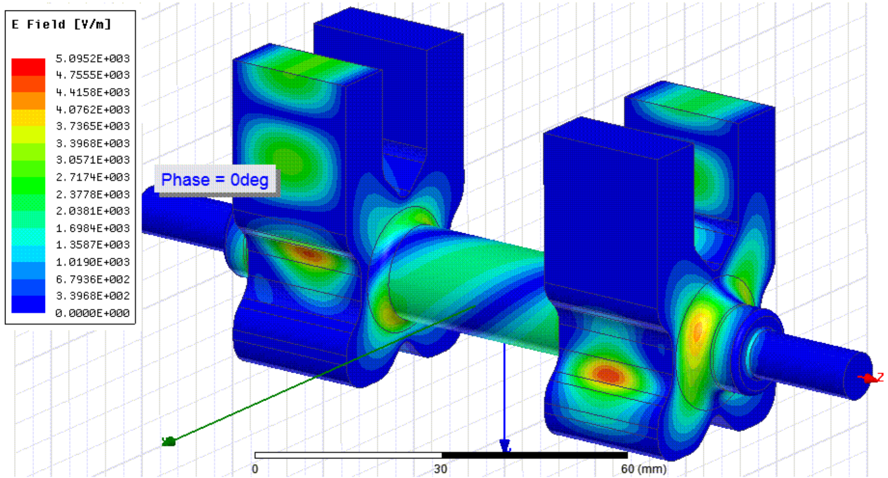


Phase difference between port 1 and port 2:

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

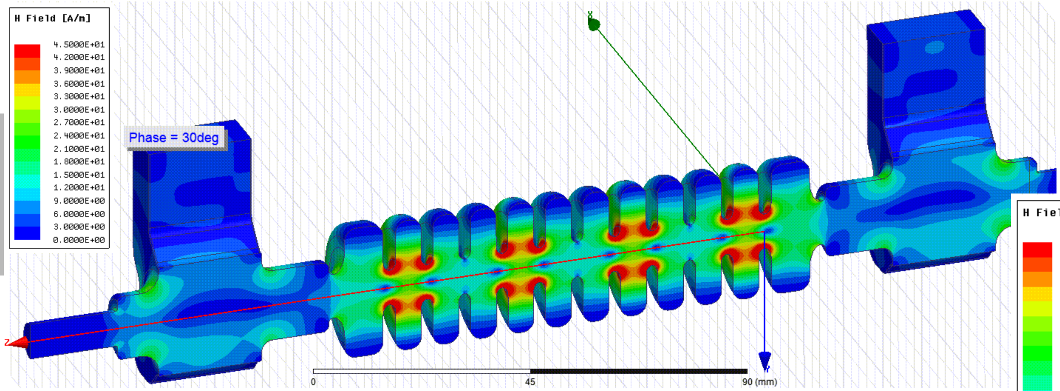


Full geometry for a face-to-face RF check of two E-rotators



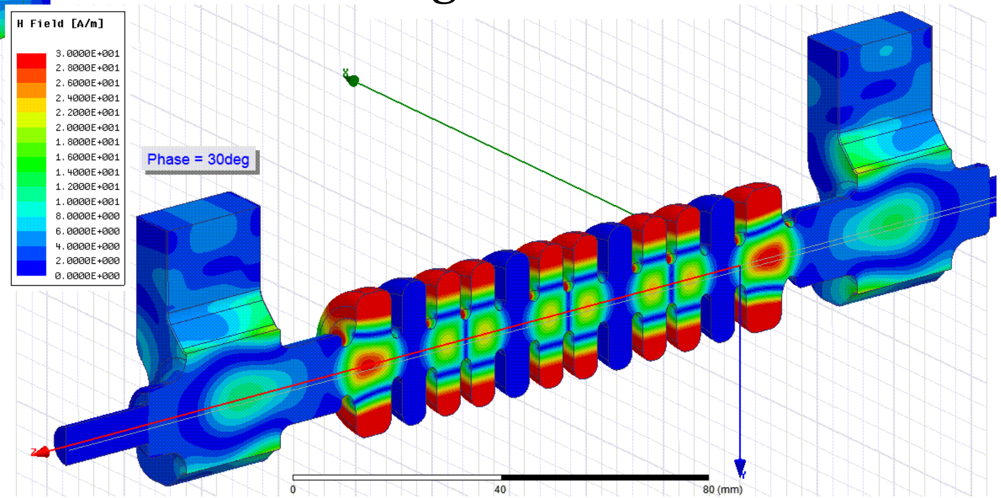
A. Grudiev, CLIC-note-1067 (2016).

PolariX TDS: tolerance



Electric Field

Magnetic Field



- ❑ The structure supports only the propagation of the operating modes TM11x and TM11y at the structure operating frequency.
- ❑ **BOTH these polarizations must be synchronized with the beam**, otherwise the polarization phase will rotate and the integrated dipolar kick in the operating plane will be reduced.

Tuning may be difficult because a tight azimuthal symmetry is required!

→ Tuning free assembly procedure developed at PSI because a high azimuthal symmetry is required

Tuning-free technology at PSI

❑ **Tuning Free Assembly Procedure developed at PSI**

- PSI has developed a production line of high technological content for high-quality, high-gradient C-band accelerating structures for the SwissFEL project (120 structures)

  → Allows for maintaining the cups shape after assembly (no RF tuning needed);
- Collaboration CERN-PSI on first-tuning-free X-band Accelerating Structures: CLIC X-band prototypes (gradient ~120 MV/m)

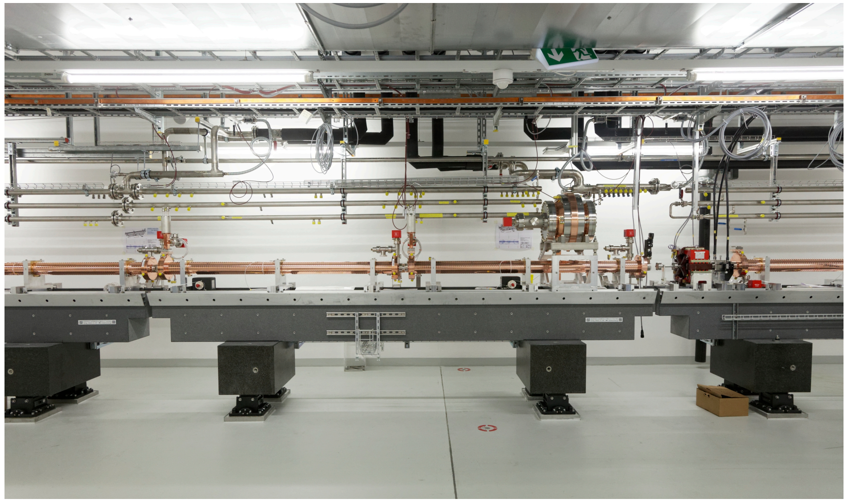
❑ **Machining precision down to 2 µm** can be obtained for the cups (PolariX TDS tolerance: 2 µm ↔ 5% V kick loss)

❑ **Max deviation of cups from straight trajectory** usually **< 20um** (PolariX TDS tolerance ~ 200um)

CONSOLIDATION AND EXTENSION OF THE HIGH-GRADIENT LINAC RF TECHNOLOGY AT PSI

P. Craievich*, M. Bopp, H. Braun, A. Citterio, H. Fitze, T. Garvey, T. Kleeb, F. Loehl, F. Marcellini, M. Pedrozzi, J.-Y. Raguin, L. Rivkin, K. Rolli, R. Zennaro
Paul Scherrer Institut, 5232 Villigen PSI, Switzerland

Linac conference 2018



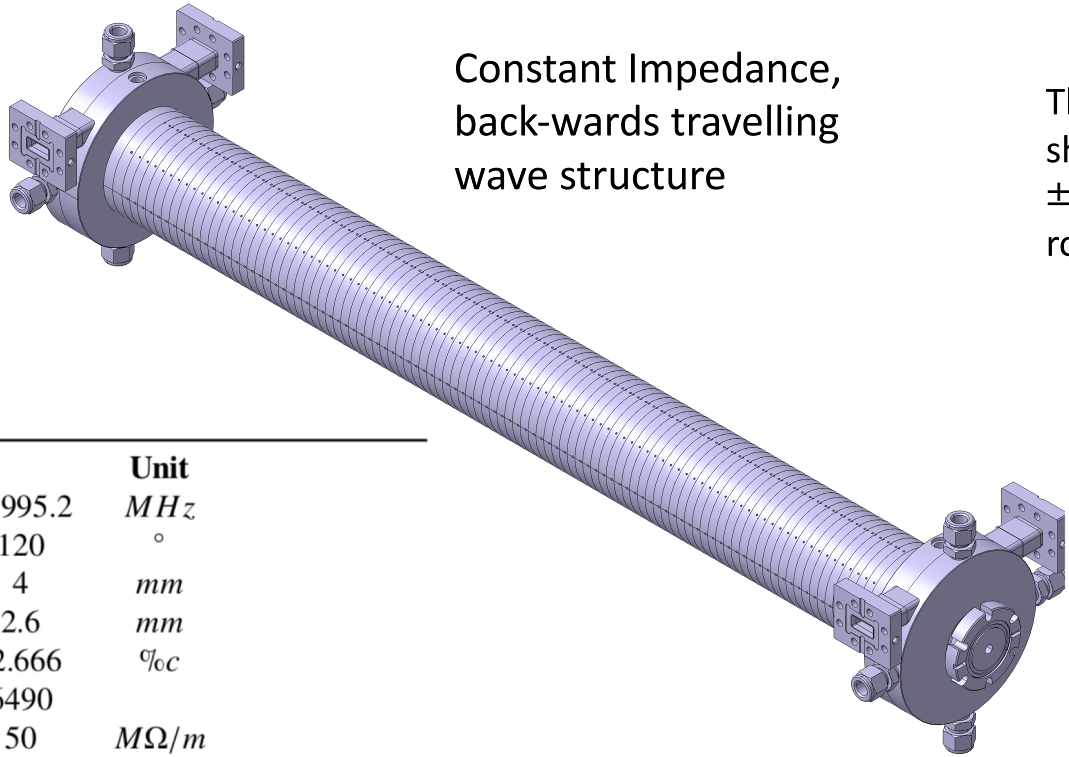
DESY-CERN-PSI Collaboration

- Goal: Develop PolariX TDS with variable polarization
- Cavity design and tolerance study were performed by CERN
- Common mechanical design of the cavity fulfills the requirements of many experiments. Consolidation of the RF technology developed at PSI
  - ATHOS beamline at SwissFEL
  - FLASHForward, FLASH2, SINBAD at DESY. XFEL observer of the project
- Cavity will be assembled at PSI using the tuning free assembly procedure (2018).
- Test of the prototype cavity with beam at DESY (FLASHForward beamline, 2019).
- After successful test of the prototype **six other cavities will be produced** for the experiments (starting in 2019).

Parameters of X-band TDS for different projects

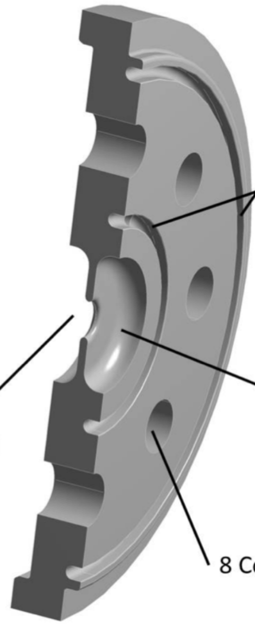
Parameters	SINBAD	FLASH II	FLASHForward	ATHOS SwissFEL	Unit
Charge	0.5-30	20-1000	20-500 (driver) 10-250 (witness)	10-200	pC
Norm. emit. (rms)	0.1-1	0.4-3	2.0-5.0 (driver) 0.1-1.0 (witness)	0.3	mm
Bunch length (rms)	0.2-10	<3-200	50-500 (driver) 1-10 (witness)	2-30	fs
β function @TDS	10-50	7-20	50-200	50	m
Beam energy	80-200	400-1400	500-2500	3400	MeV
Rep. rate	10-50*	10**	10**	100*	Hz
TDS voltage	25-40	30-45	25-30	30-60	MV
# TDS	2	2	1	2	
Max. length	3	<1.91(8)	<2	4	m
TDS iris	4	4	4	4	mm
TDS frequency	11991.6	11988.8	11988.8	11995.2	MHz
Temperature	48	62	62	25-35	°C

First Prototype



Constant Impedance, back-wards travelling wave structure

The inner profiles of the cups should be within the tolerance of ±3 µm with an average surface roughness Ra below 25 nm.

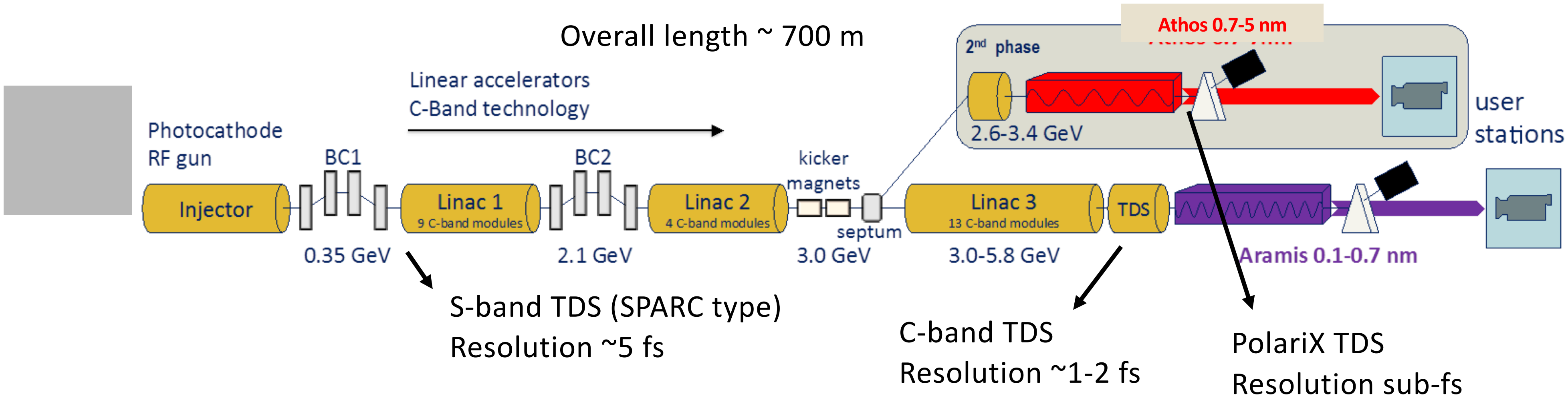


Cell parameter		**Unit**	
Frequency	11995.2	MHz	
Phase advance/cell	120	°	
Iris radius	4	mm	
Iris thickness	2.6	mm	
Group velocity	-2.666	$\%c$	
Quality factor	6490		
Shunt impedance	50	$M\Omega/m$	
TDS parameter	**Short**	**Long**	**Unit**
n. cells	96	120	
Filling time	104.5	129.5	ns
Active length	800	1000	mm
Total length	960	1160	mm
Power-to-voltage	5.225	6.124	$MV/MW^{0.5}$
TDS + BOC	**Short**	**Long**	**Unit**
BOC Q_0	145000	145000	
BOC β@t_k=1.5μs	7	7	
Power-to-voltage	12.010	13.626	$MV/MW^{0.5}$

- Currently in production at PSI
- Bead-pull measurements will be performed by this year at PSI in order to verify that the polarization of the dipole fields does not have any rotation along the structure

Applications for fs/sub-fs time-resolved measurements based on a variable polarization X-band TDS system

Post-undulator PolariX TDS for Athos line 1/4



Main parameters	
Wavelength from	0.1 nm–5 nm
Photon energy	0.2-12 keV
Pulse duration (rms)	1 fs - 20 fs
e^- Energy (0.1 nm)	5.8 GeV
e^- Bunch charge	10-200 pC
Repetition rate	100 Hz

ARAMIS

Hard X-ray FEL, λ=0.1 - 0.7 nm (12-2 keV)

Linear polarization, variable gap, in-vacuum undulators

Reached nominal parameters:

→ electron beam energy 5.8 GeV

→ photon energy 12 keV

Completed 8 out of 12 pilot experiments

User operation from January 2018

ATHOS

Beam Energy 2.7 – 3.3 GeV

Soft X-ray FEL, λ=0.65 - 5.0 nm (2-0.2 keV)

Variable polarization with Apple-X undulators and chicane

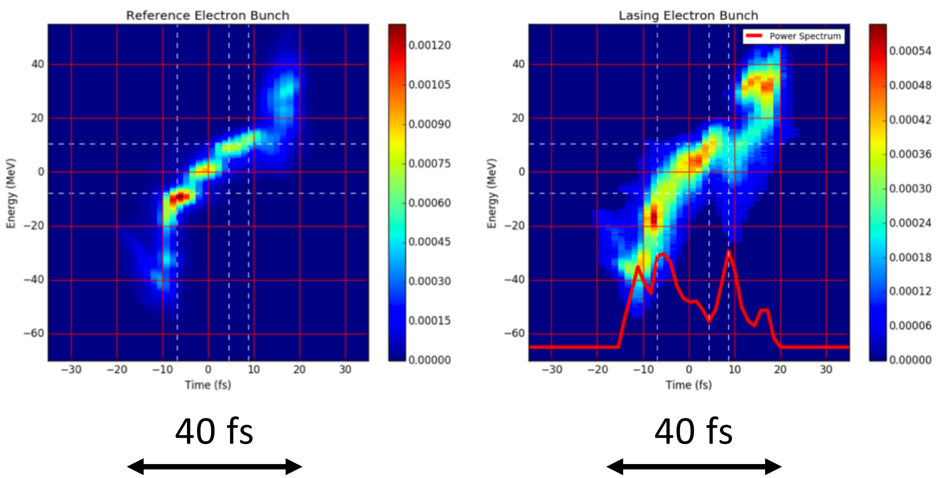
First Pilot experiment end 2020

PolariX TDS for Athos line 2/4

Requirements for Athos line

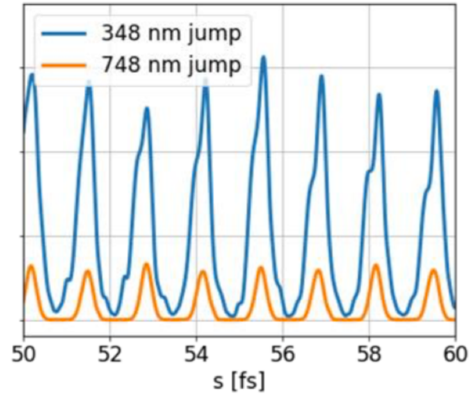
- Good electron beam quality in terms of energy spread, emittance, and peak current
- Time-resolved (i.e. longitudinal) information and control of these parameters (linear compression)
- Measurement and tunability of electron and photon pulse lengths (improvement of FEL performance):

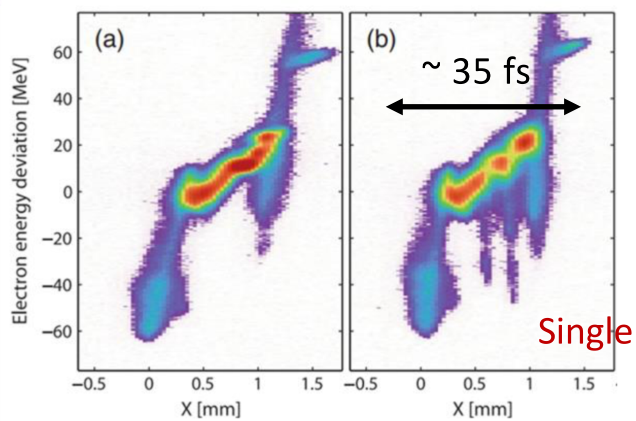
Spectral and temporal characterization of two color mode of operation
(figure courtesy of A. al Haddad and C. Bostedt)



Characterization and monitoring of intense attosecond pulses
(figure courtesy of A. Lutman, PRL 120, 2018)

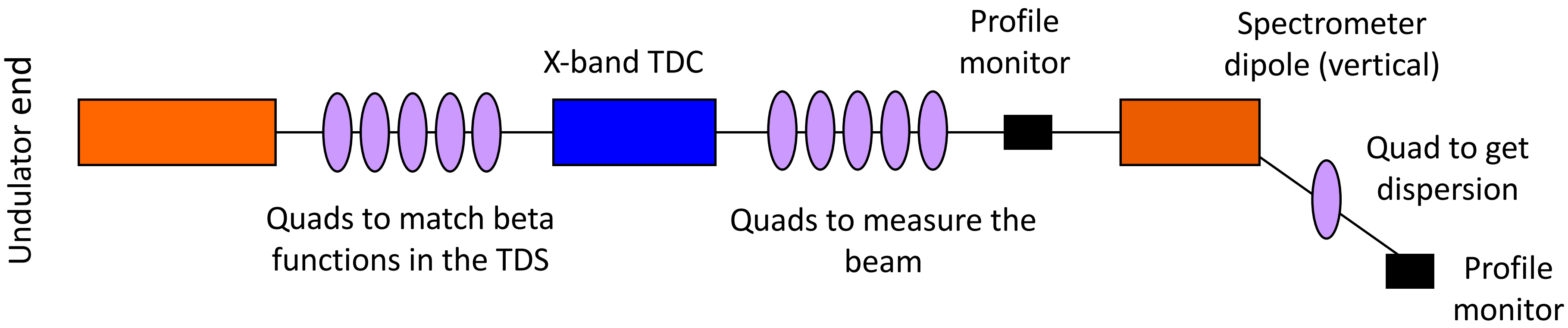
Ability to measure attosecond pulse trains
(figure courtesy of E. Ferrari)



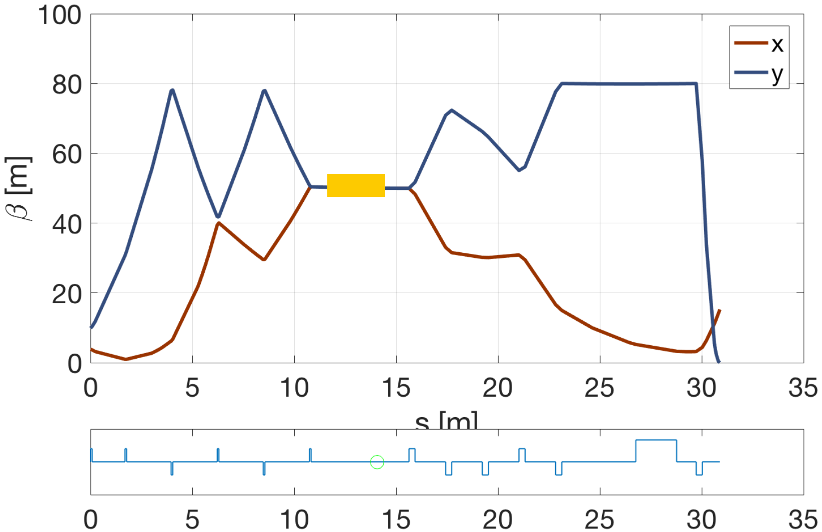


PolariX TDS for Athos line 3/4

Measurement concept



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

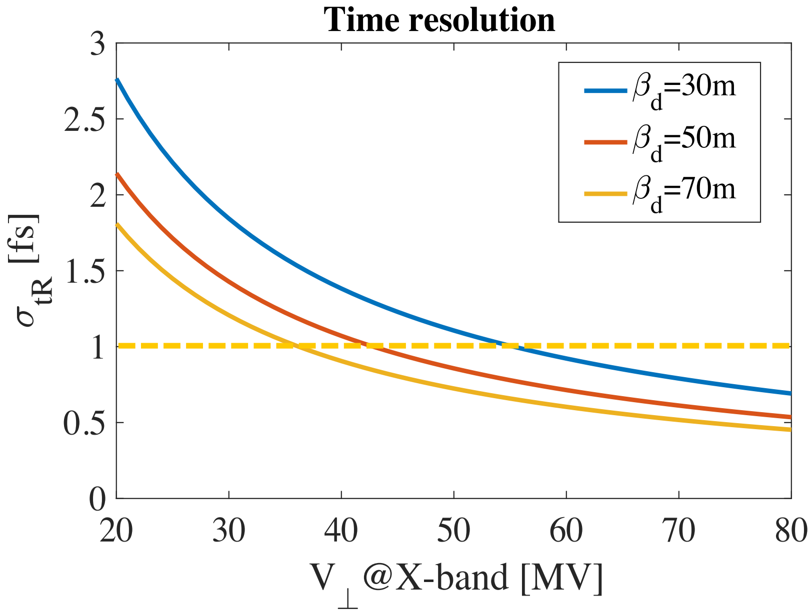


Beam measurements:

- ❑ Slice emittance on both planes
- ❑ Projected emittance on both planes
- ❑ Electron and photon pulse length
- ❑ Energy spread induced by FEL process

courtesy of E. Prat

PolariX TDS for Athos line – resolution 4/4

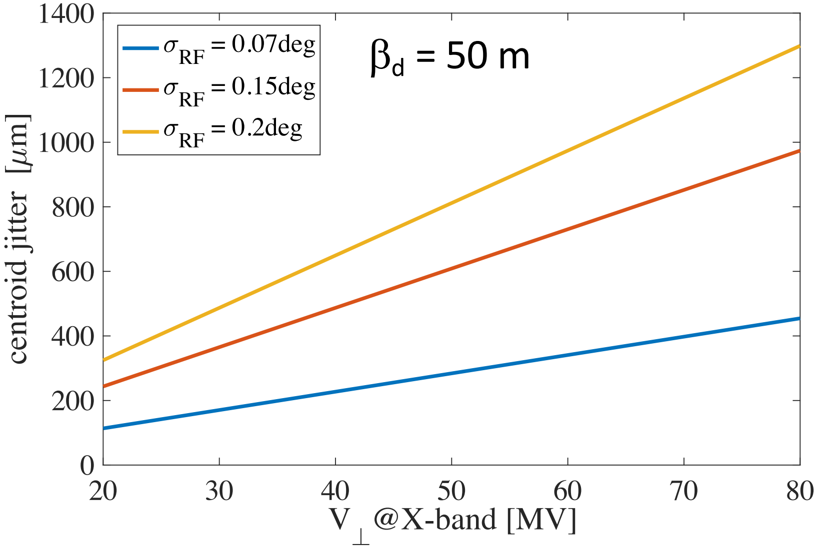


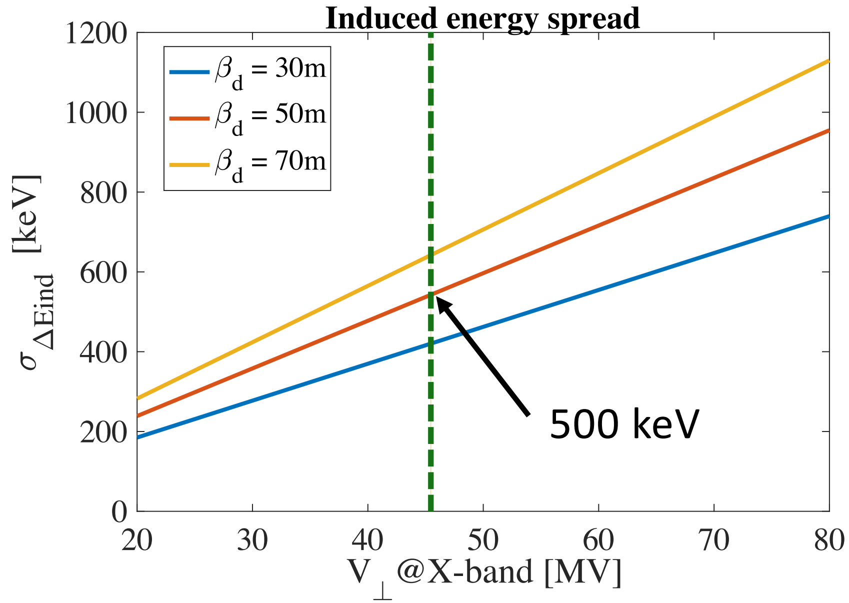
$$\sigma_{t,res} = \frac{\sqrt{\varepsilon_N} \cdot E_0 \cdot \sqrt{\gamma}}{\sqrt{\beta_y} \cdot \sin \Delta\psi_{ds} \cdot eV_\perp \cdot c \cdot k_{rf}}$$

Resolution 0.95 fs @45MV and β_d = 50 m

Resolution 0.5 fs @80MV and β_d = 50 m

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

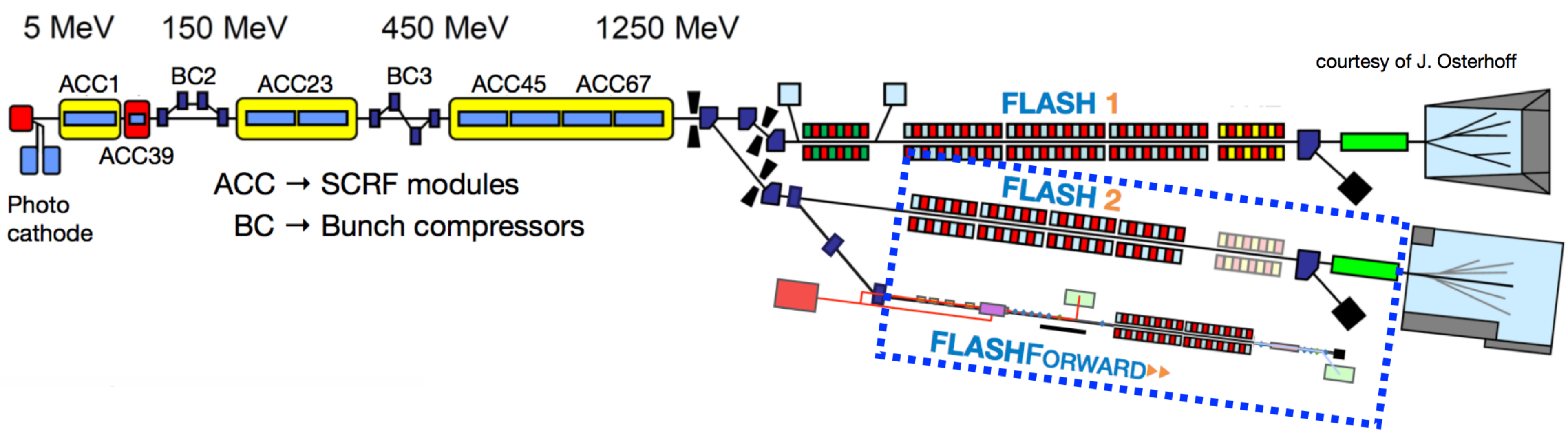




Applications at DESY/FLASH II/FLASHForward

Experiments at DESY interested in high-gradient X-band TDS:

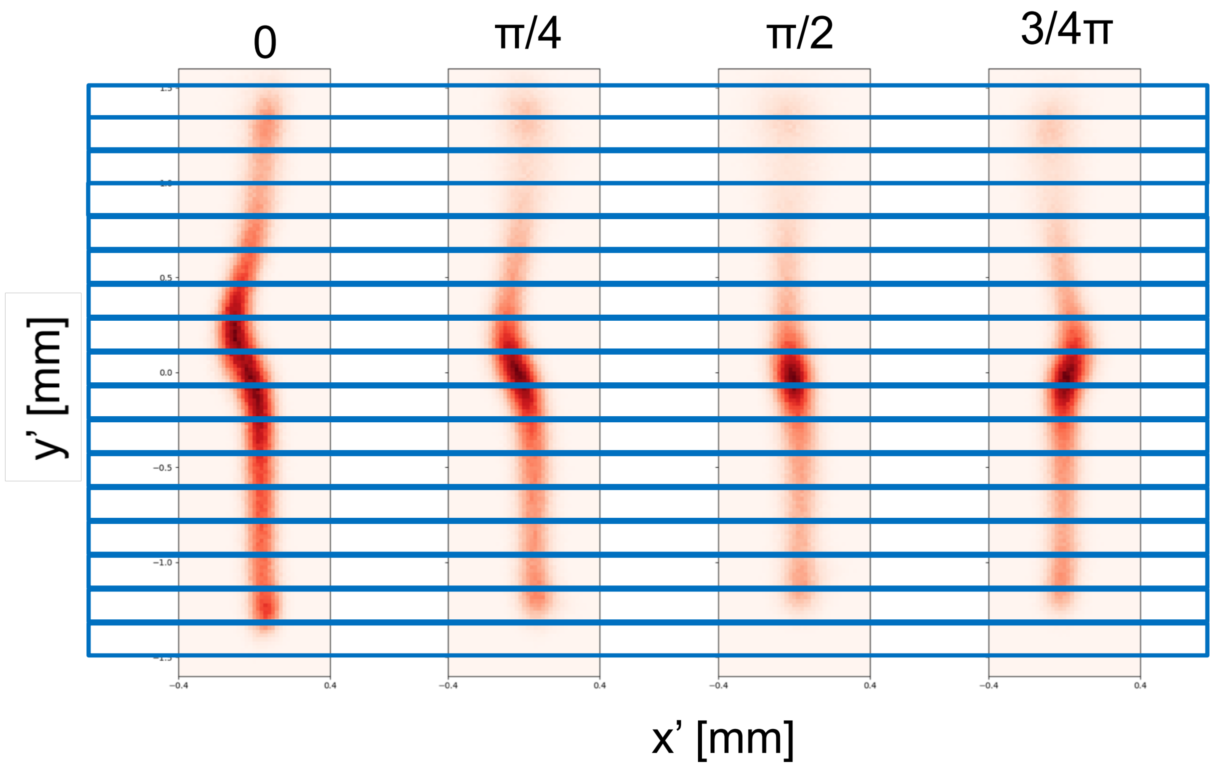
- post-undulator diagnostics at FLASH2 (FEL emission): measurements of the longitudinal phase space and energy spread induced by FEL lasing (single-shot)
- Diagnostics for plasma wakefield acceleration at FLASHForward, project aims to accelerate electron beams to GeV energies over a few centimeters in plasma.
  - pulse duration of accelerated beams is typically in the few fs range



Courtesy of F. Christie (FLASH2) and R. D'Arcy (FLASHForward)

FLASHForward: Tomographic Reconstruction 1/2

- 4 *xy* screen profiles [2D] out of 16.
  - Convert *y'* to *t* and divide into slices (0.85 fs) [2D]



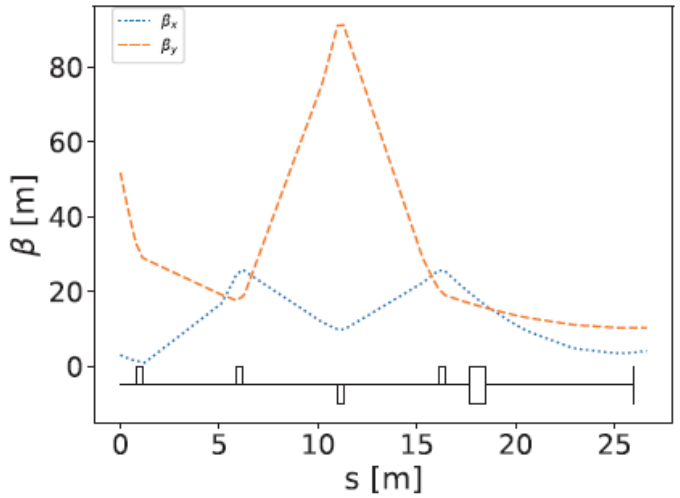
Screen resolution

10-20μm.

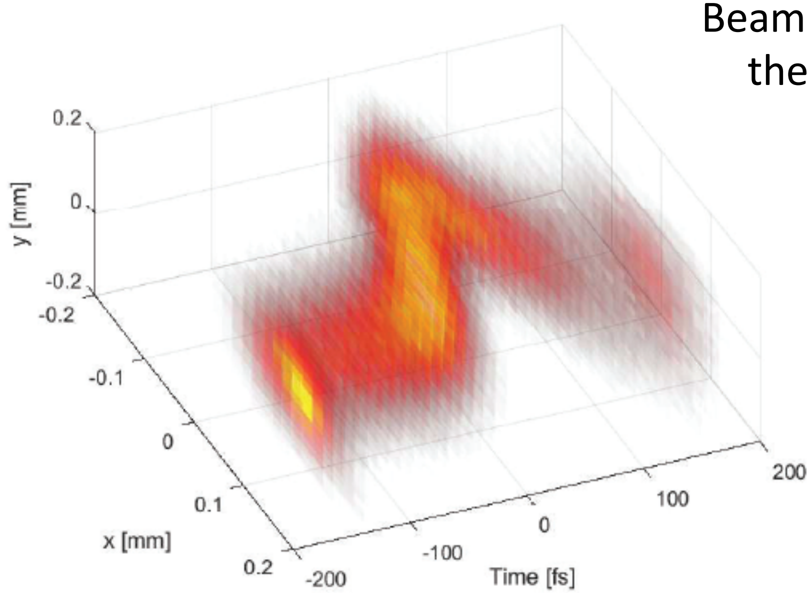
  - For each slice, take projection on *x'* axis [1D] and combine using tomographic reconstruction (SART algorithm) [2D]
  - Stack slices [3D]

D. Marx et al. WEPAF050 IPAC18

FLASHForward: Tomographic Reconstruction 2/2



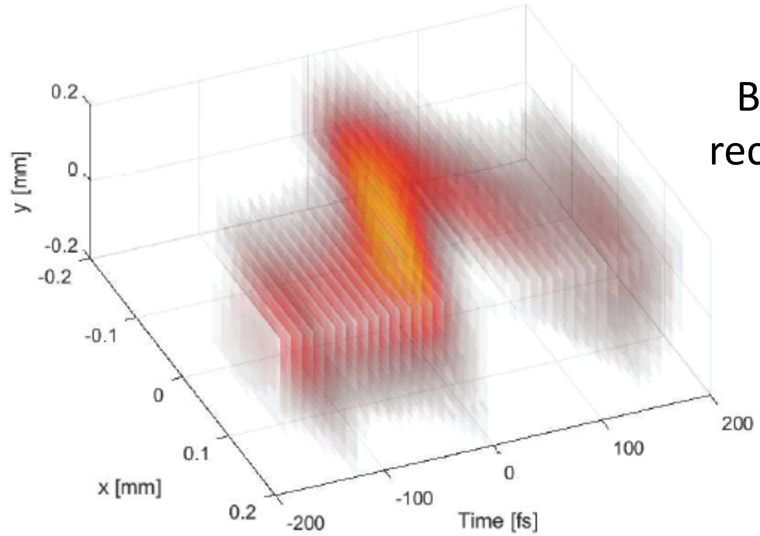
Beam distribution at the measurement screen



$$R_t \approx \frac{\sigma_y^{\text{off}}|p|c}{2\pi f e V_0 L}$$ ⇨ V_0=14 MV

R_t~10 fs

Beam distribution reconstructed from the simulated measurement



Simulation done using Elegant

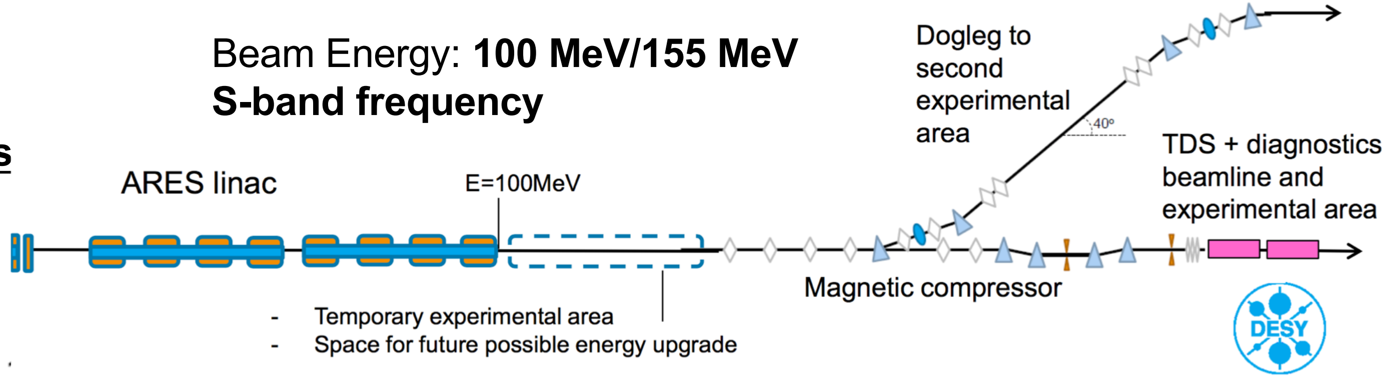
D. Marx et al. WEPAF050 IPAC18

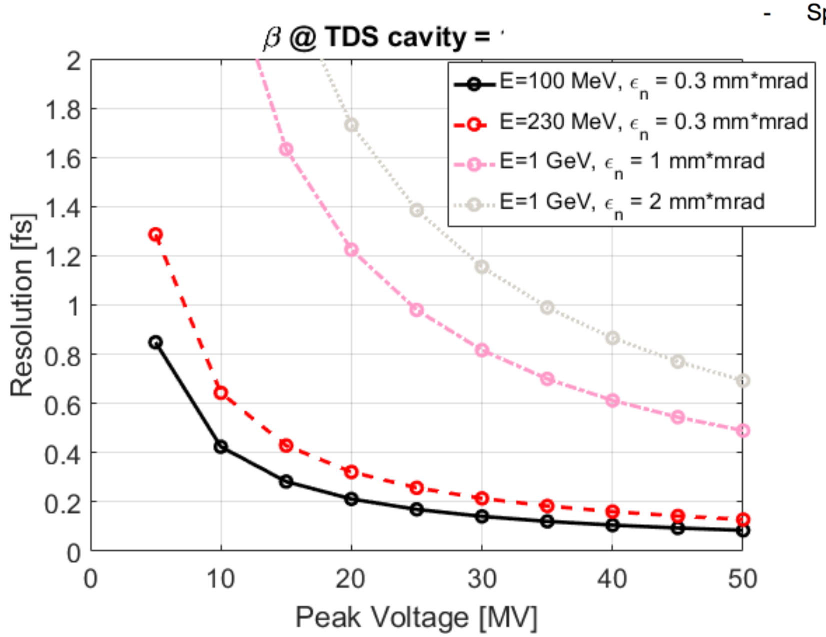
Applications at DESY/SINBAD 1/2

- characterization of ultra-short (fs/sub-fs) electron bunches for injection on novel high gradient acceleration techniques: acceleration in THz laser driven dielectric structures, Dielectric Laser Acceleration, Laser Driven Wake-Field Acceleration

Bunch charge : **0.5-30 pC**
Bunch length : **<u>sub-fs/few fs</u>**
ε_N< **0.5mm*mrad**

Beam Energy: **100 MeV/155 MeV**
S-band frequency





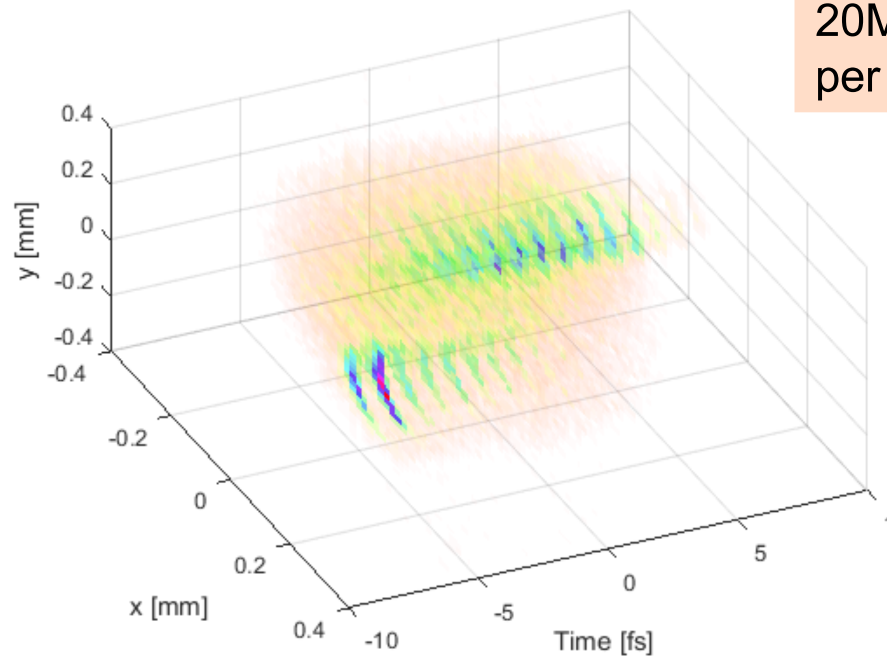
200 as goal resolution for ultra-short bunches characterization

Courtesy of B. Marchetti

SINBAD - Tomographic Reconstruction 2/2

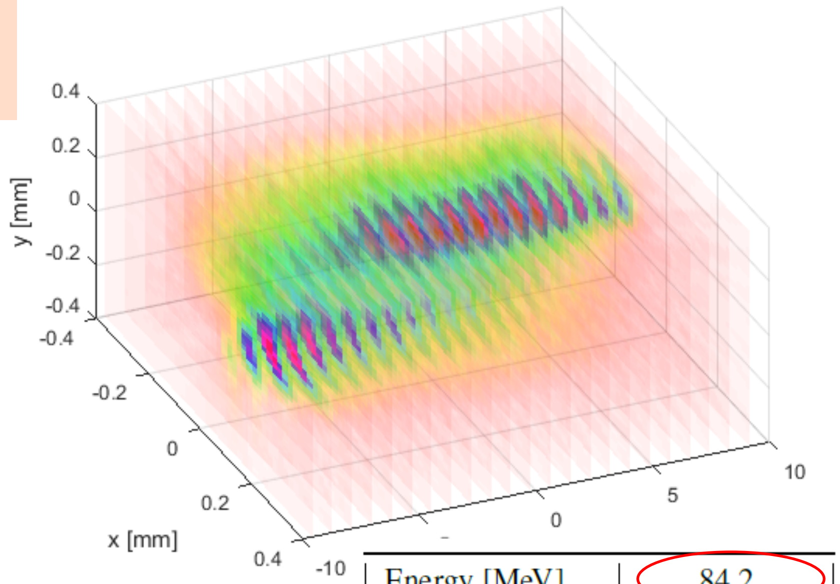
- Novel measurement technique for 3D e-bunch charge reconstruction currently under study at DESY which makes special use of the variable polarization TDS

Actual 3D e-beam distribution at the screen location



20MV kick per cavity

Reconstructed 3D distribution



Energy [MeV]	84.2
Charge [pC]	3
σ_t [fs]	5.15
$\sigma_{x/y}$ [μm]	87.9 / 96.8
$\epsilon^{norm}_{x/y}$ [mm mrad]	0.224 / 0.190
$\beta_{x/y}$ [m]	5.69 / 8.14
$\alpha_{x/y}$	-0.377 / 0.258

- Sixteen streaking angles (only 1 calibration needed)
- Simulations in elegant

D. Marx et al., J. Phys.: Conf. Ser., vol. 874, p. 012077, (2017);

References for PolariX TDS applications

- **FLASHForward**
  - R. D’Arcy et al., Proc. of IPAC18, paper TUPML017, (2018);
- **FLASH2**
  - F. Christie et al., Proc. IPAC’17, paper WEPAB017, (2017);
- **SINBAD-ARES**
  - D. Marx et al., J. Phys.: Conf. Ser., vol. 874, p. 012077, (2017);
  - D. Marx et al., J. Phys.: Conf. Ser., vol. 874, p. 012078, (2017);
  - D. Marx et al., Nucl. Inst. And Meth, A (2018);
- **ATHOS**
  - P. Craievich et al., Proc. FEL’17, paper WEP040, (2017).

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STATUS OF THE PolariX-TDS PROJECT

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Credits: In this talk I have summarized studies done within the PolariX TDS Collaboration.

To prepare my slides, I have especially used material from: A. Grudiev, B. Marchetti and D. Marx.

Thank you for the attention!!