Application of CLIC X-band technology for beam diagnostics at DESY

B. Marchetti
On behalf of DESY team
CLIC workshop 2017

Team working on application of X-band technology at DESY:
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HELMHOLTZ | ASSOCIATION

DESY

Outline

- Introduction
- Experiments at DESY interested in high gradient X-band TDS
- Variable Polarization TDS and 3D Reconstruction of the Bunch Charge Distribution
- Summary and Outlook

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Transverse Deflecting Structures and Crab Cavities

Many Applications like:
- *Rotate particle beams in colliders*
- *Particle beam manipulation (e.g. emittance exchange techniques)*
- *Longitudinal particle beam diagnostics*
- *Etc.*

Working Principle:

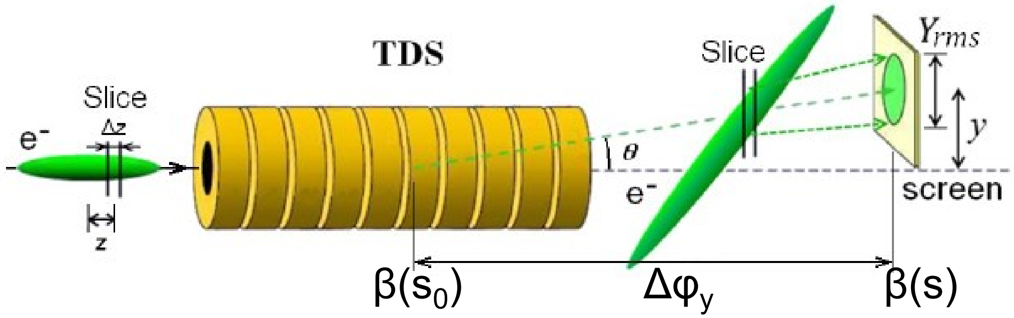


Fig. Credits: D. Malyutin PhD thesis

Longitudinal Resolution for use as <u>diagnostic device</u>:

$$\mathcal{R}_{t,e} = \frac{\sigma_{y0}}{S_y} = \frac{\sqrt{\beta_y(s)\varepsilon_y}E}{\sqrt{\beta_y(s)\beta_y(s_0)}\sin(\Delta\phi_y)e\omega V_y}$$

e-bunch:
- Energy E
- Vertical emittance ε_y

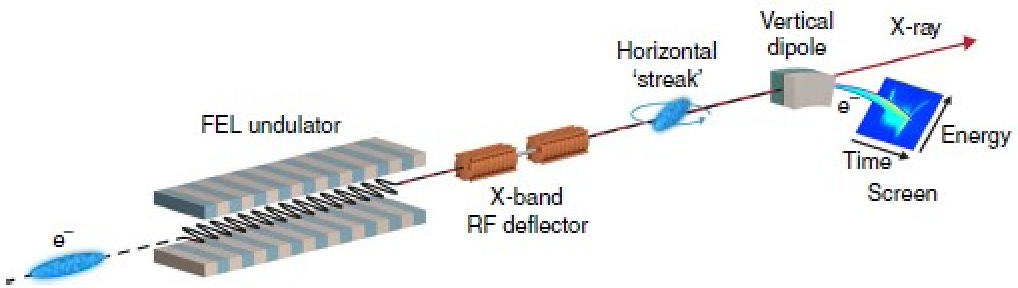
RF cavity:
- Frequency f = ω/(2π)
- Peak deflection voltage V_y

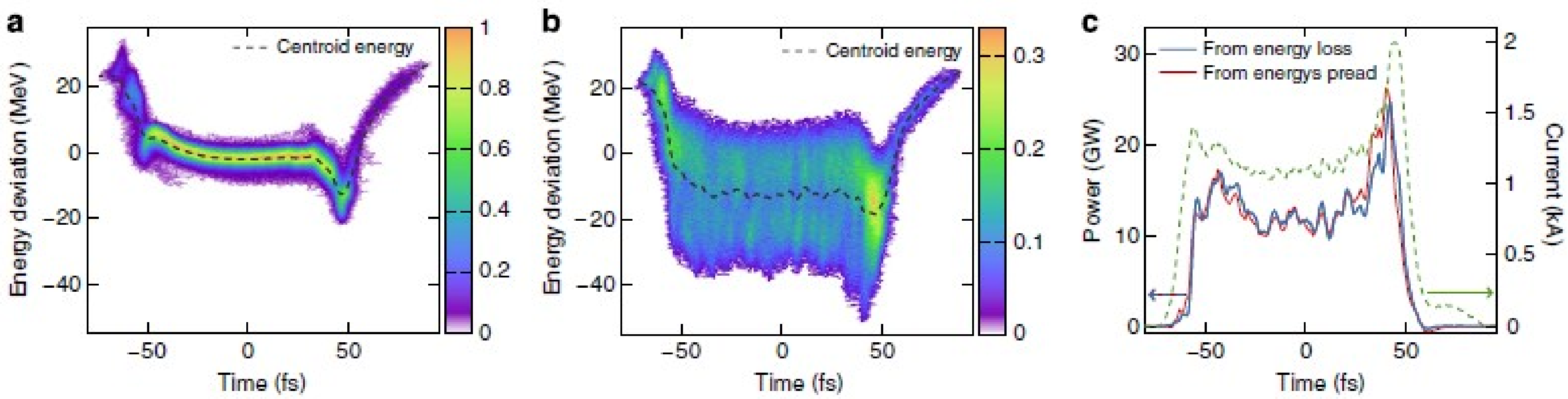
Frequency **~12GHz (X-band)** allows having 4 times higher resolution than **~3GHz (S-band)**

Cfr: P. Emma et al., LCLS-TN-00-12
M. Röhrs et. al., PRSTAB 12 050704 (2009)

State of the Art of X-band TDS systems

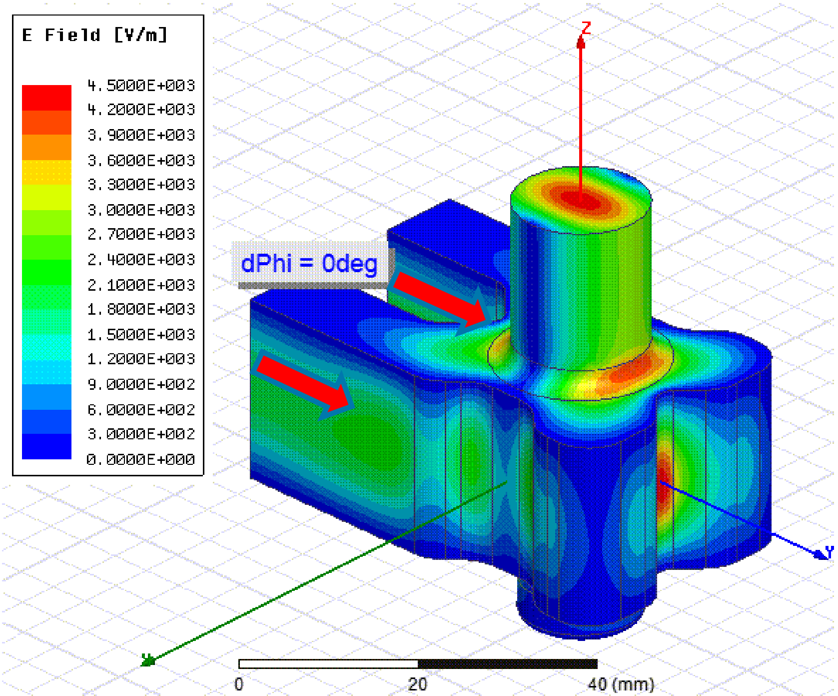
- Measurement of the energy spread induced by the FEL process at SLAC
- Achieved **temporal Resolution < 1fs** for soft X-rays





C. Behrens et al., „Few-femtosecond time-resolved measurements of X-ray free electron laser" , Nat. Comm. 4762 (2014).

Beyond the State of the Art: TDS with Variable Polarization of the Deflecting Field



Variable Polarization Circular TE11 Mode Launcher

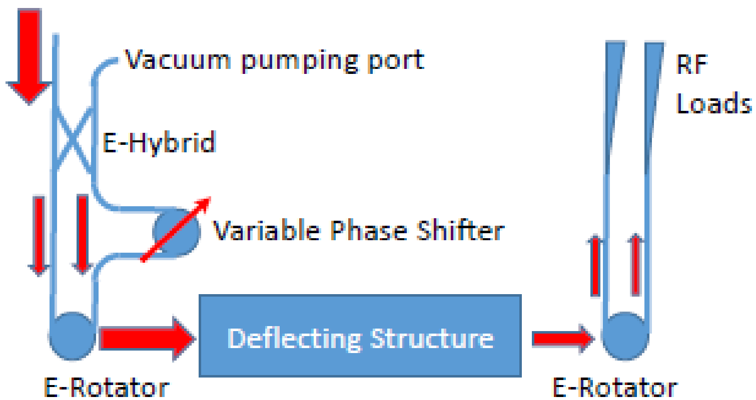
Courtesy of A. Grudiev

Very precise azimuthal symmetry required!

→ Tuning free assembly procedure developed at PSI

Phase difference between port 1 and port 2:

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



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

Ongoing efforts towards building an international collaboration to build and test the first prototype

Collaboration Agreement in preparation

DESY PSI PAUL SCHERRER INSTITUT CERN

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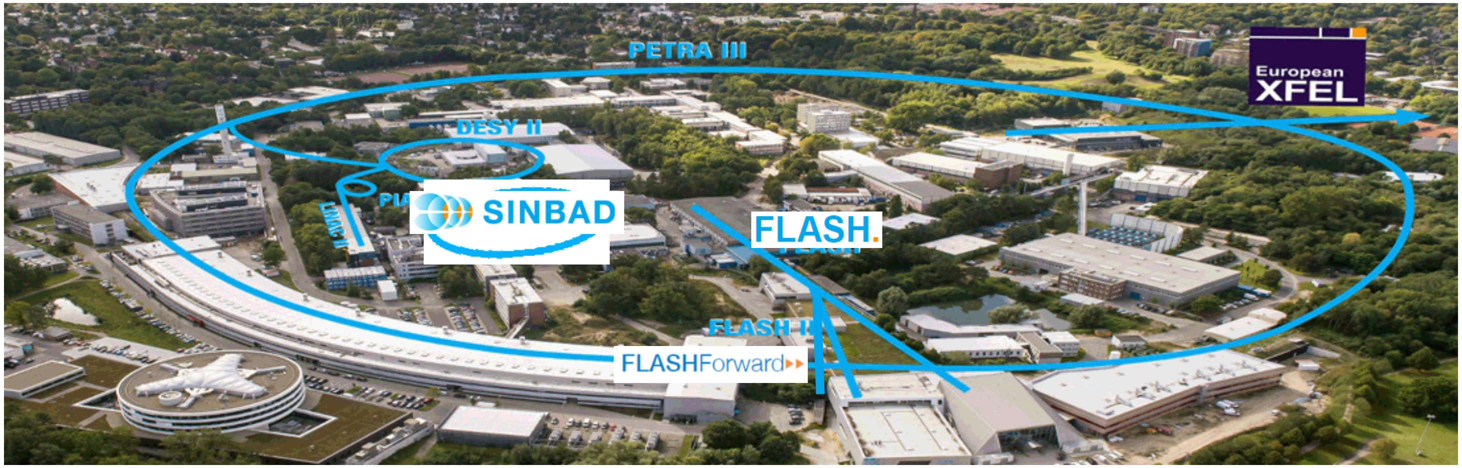
Overview of the DESY campus in Hamburg



> Many experiments are interested in the procurement of a X-band TDS system for different kind of applications:

- **FLASH2**: measurement of the energy spread induced by FEL lasing
- **FLASHForward**: characterization of driver and witness electron beams in PWFA
- **SINBAD**: characterization of ultra-short (fs / sub-fs) electron bunches for injection on novel high gradient acceleration techniques.

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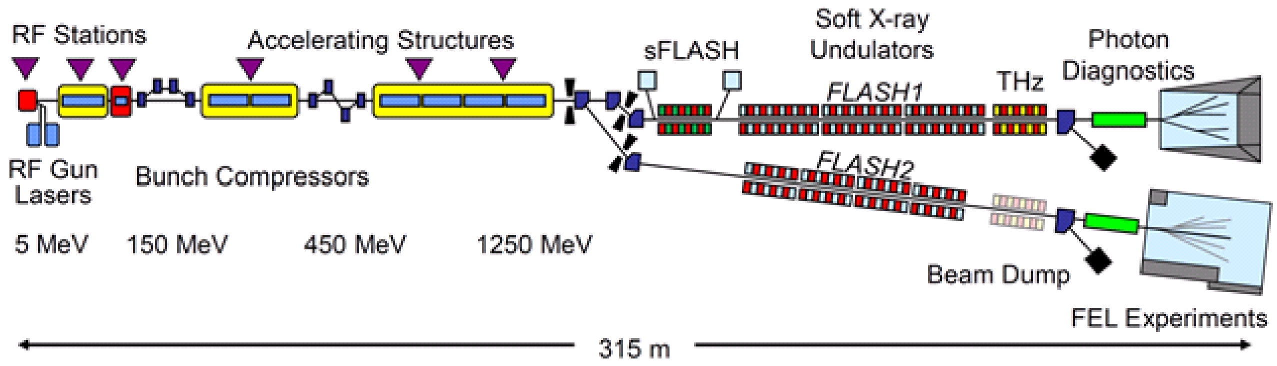
FLASH

> Superconducting linear accelerator delivering soft x-ray FEL radiation for users



> Long bunch trains, up to 800 bunches (1 MHz) 10 times per second

> FLASH2 commissioned in 2014 (more photon beam lines), operated simultaneously with FLASH1

> Peak brilliance: $10^{28} - 10^{31} \frac{\text{photons}}{\text{s mrad}^2\text{ mm}^2\text{ 0.1\%bw}}$

> Pulse duration: $< 30 - 200$ fs (FWHM)

> Short pulse operation mode with special injector laser

- Possible to produce electron bunches with $\sigma_t < 3$ fs

Courtesy of F. Christie

Parameters for FLASH2

- So far, no hardware available for direct longitudinal phase space diagnostics
- Two operation modes possible (electrons):

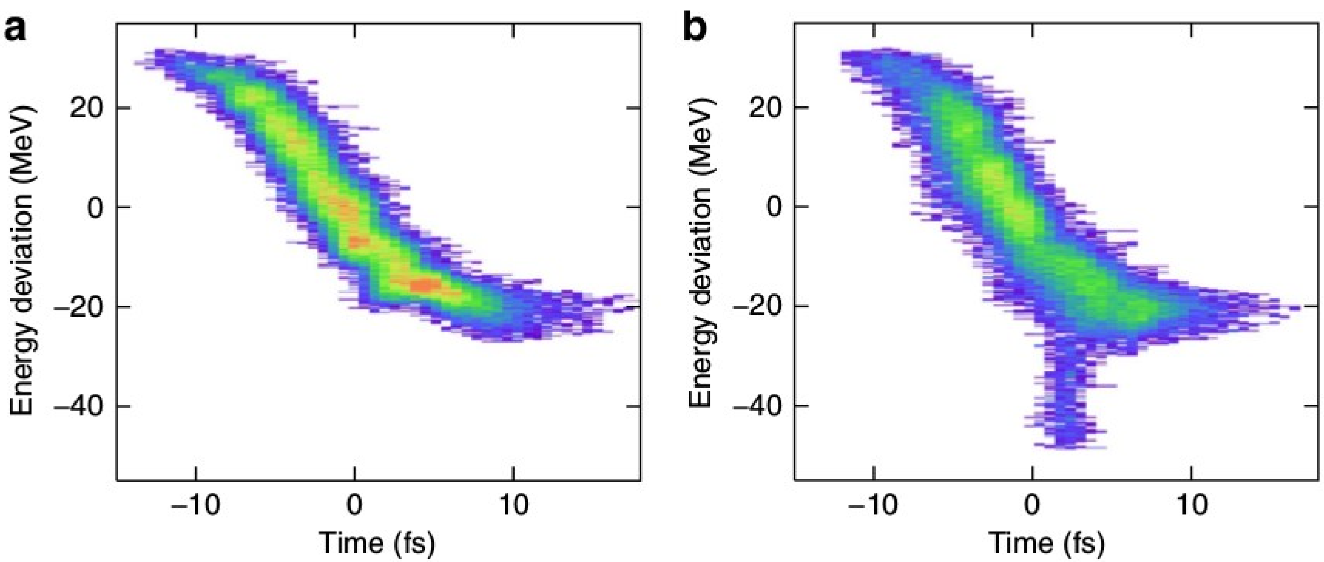
- High charge
  - $E = 0.4 - 1.2\ \text{GeV}$
  - $Q = 0.1 - 1\ \text{nC}$
  - $\sigma_t = 50 - 200\ \text{fs}$
  - $\epsilon_N = 1 - 3\ \text{mm mrad}$
- Resolution should be $\sim 5\ \text{fs}$

- Short pulse
  - $E = 0.4 - 1.2\ \text{GeV}$
  - $Q = 20 - 100\ \text{pC}$
  - $\sigma_t =< 3 - 50\ \text{fs}$
  - $\epsilon_N = 0.4 - 1\ \text{mm mrad}$
- Resolution $< 1\ \text{fs}$ for nice beam desired

Courtesy of F. Christie

Photon Pulse Characterization using TDS

- X-band TDS deflection (vertical) combined with horizontally deflecting dipole to obtain longitudinal phase space
- Placed after undulator to gain information about lasing process
  - Which part of the bunch contributed to the lasing process?
  - Estimation of the photon pulse duration
  - Photon pulse profile reconstruction



Lasing off

Lasing on

C. Behrens *et al.*, Nat. Commun. **5**, 2014

Measurement done at SLAC

Courtesy of F. Christie

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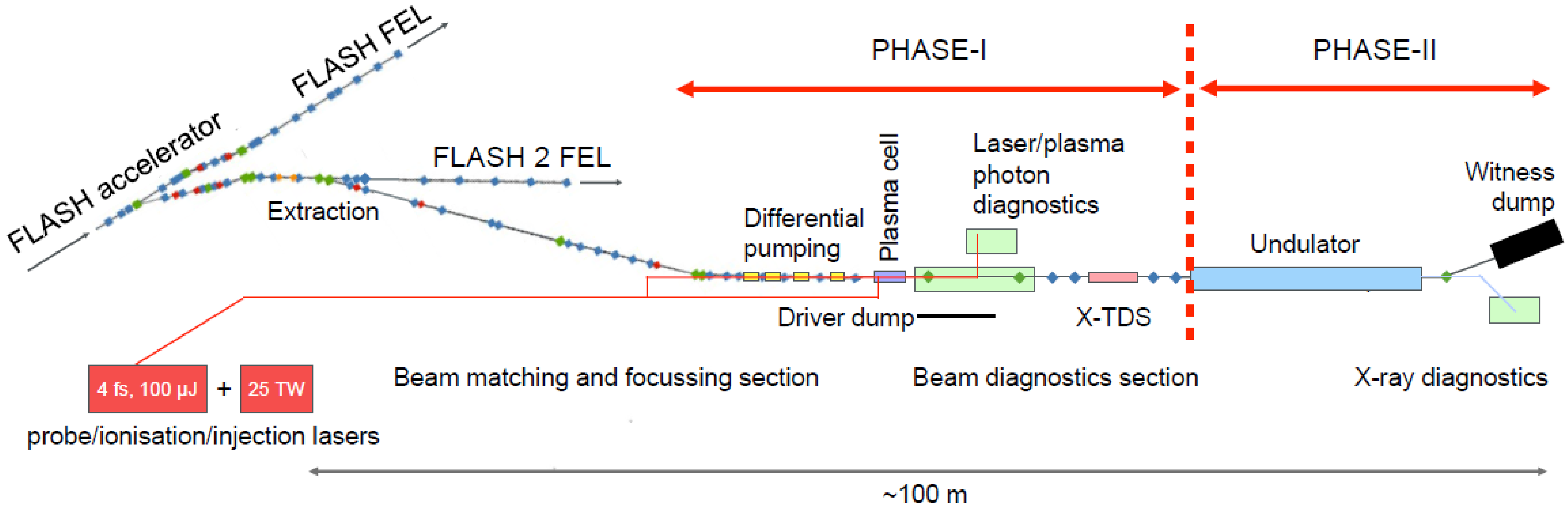
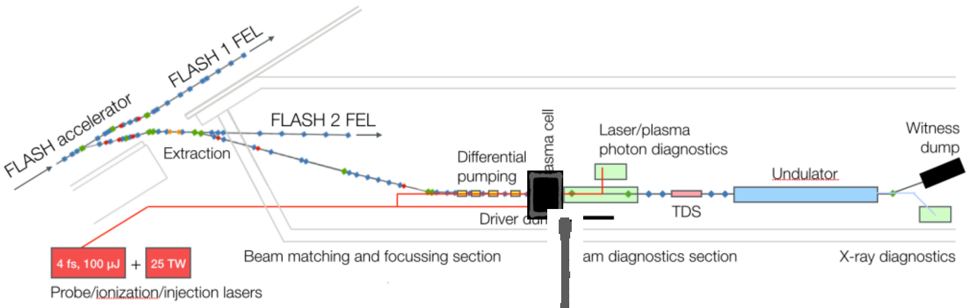
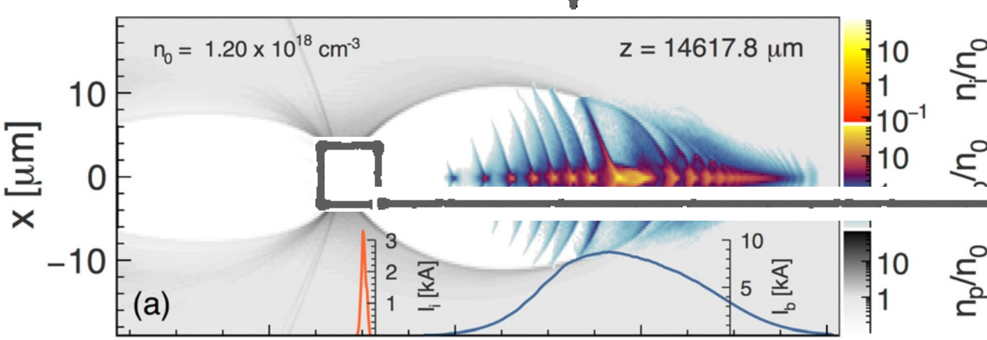
FLASHForward▸▸ overview

- FLASHForward▸▸ aims to accelerate electron beams to GeV energies over a few centimetres of plasma.
- To optimise this acceleration process it is essential to know the longitudinal properties of the drive-beam.
- Equally as important is the ability to resolve the longitudinal properties of the witness-beam, both to determine the nuances of individual injection methods, as well as to study the quality for FEL use.



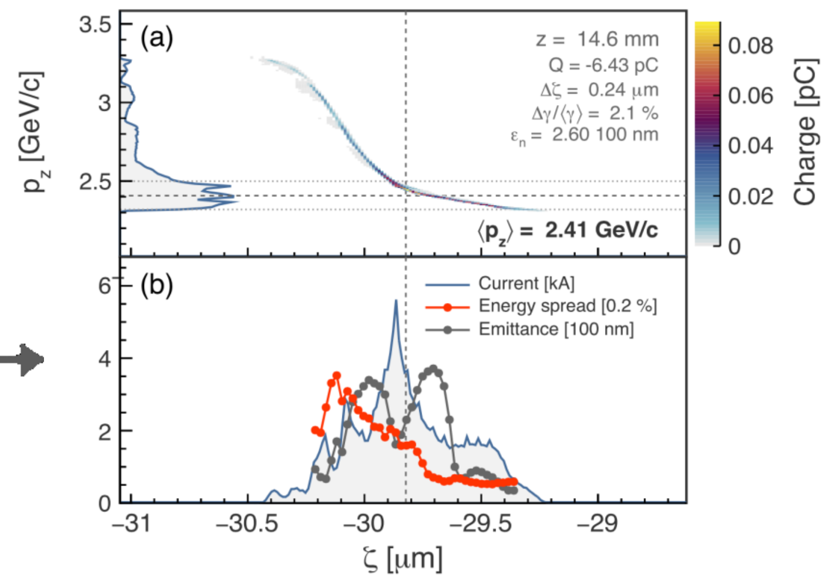
Courtesy of R. D'Arcy





Need to resolve beams spanning a longitudinal regime of three orders of magnitude:
~0.5—500 fs

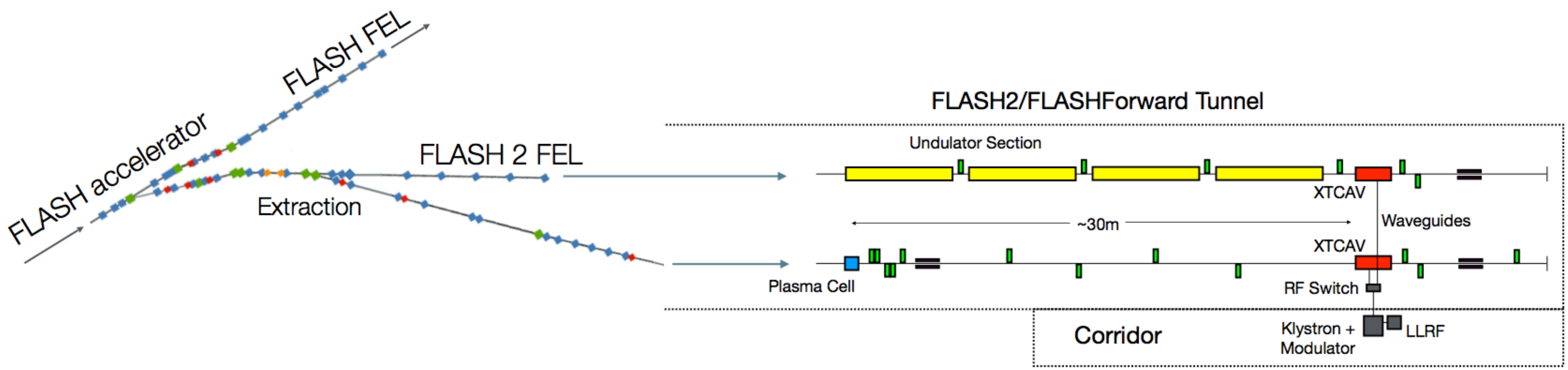
Ionisation injection



> A. Martinez de la Ossa *et al.*, Phys. Rev. Lett. 111, 245003 (2013)
> A. Martinez de la Ossa *et al.*, Phys. Plasmas 22, 093107 (2015)

Courtesy of R. D'Arcy

FLASHForward▸▸ and FLASH2 shared scheme



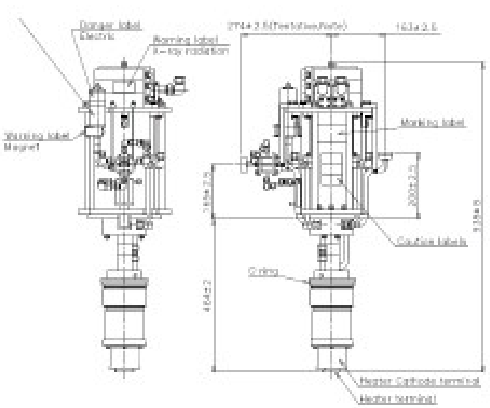
- Due to the proximity of the two beam lines, it is proposed that FLASHForward▸▸ and FLASH2 overlap schemes in order to mitigate costs, i.e. a shared LLRF source and RF unit.

- This provides a sensible solution as both experiments require X-band operation to unlock the ~fs level resolutions demanded by FEL-compatible and plasma wakefield generated bunches.

Courtesy of R. D'Arcy

X-band RF Source

- Identified solution for the RF system is the Xbox3 system operated at CERN – a 6MW Toshiba klystron with a Scandinova K200-type modulator
- With the addition of a CERN-designed SLED pulse compressor, this power could be increased to ~24 MW.
- By taking into account the loss in the waveguide (-0.1 dB attenuation per meter over 7m for FLASHForward and 11m for FLASH2) and by assuming a typical shunt impedance value for a 4mm radius X-band deflecting cavity we would have
  - a maximum voltage kick of **34MV for 2 cavities** each one 0.8m long in the **FLASH2 beamline**
  - a maximum voltage kick of **25MV for 1 cavity** 0.8 m long in the **FLASHForward beamline**



Peak power: 6.2 MW
Beam Voltage: 150 kV
Beam current: 90 A
Efficiency: 47.5%
Rep. rate: 50 Hz

Peak RF power: 8.0 MW
Pulsed voltage: 175 kV
Pulse current: 115 A
Pulse length (flat): 5 μs
Rep. rate: 10 Hz

Photo of Xbox3, courtesy of G. McMonagle

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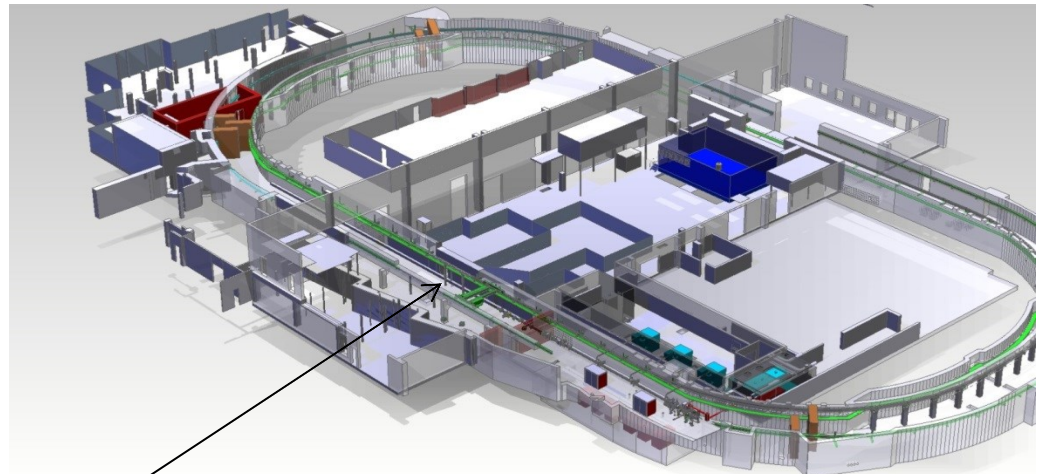
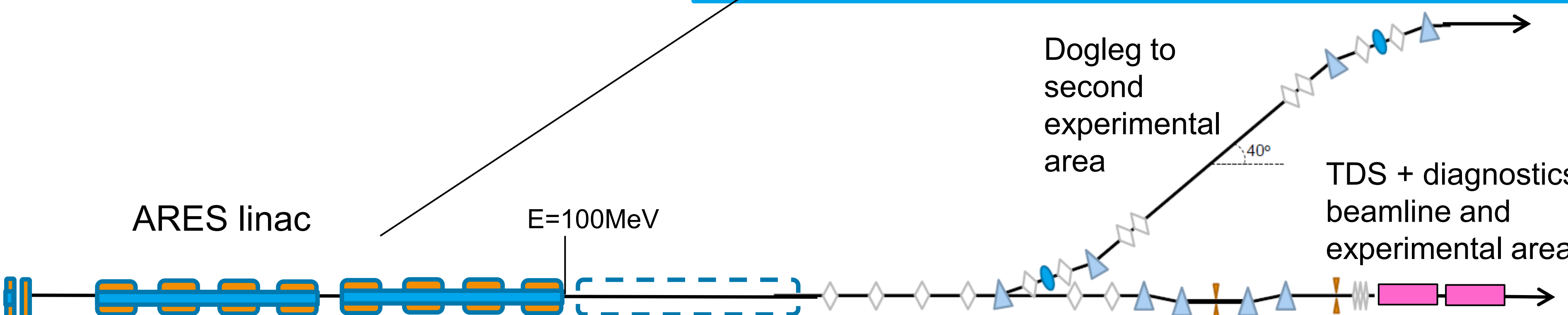
SINBAD-ARES linac

- **Short and INnovative Bunches at Desy (SINBAD)** is a **dedicated** multi-purpose accelerator R&D facility with several experiments for **ultra-fast** science and **high gradient** accelerator modules.
- **ARES (Accelerator Research Experiment at Sinbad)** is a linear accelerator for production of ultra-short bunches by using conventional RF technology
- For this experiment **longitudinal diagnostics** with **sub-fs resolution** will be **routinely** needed.

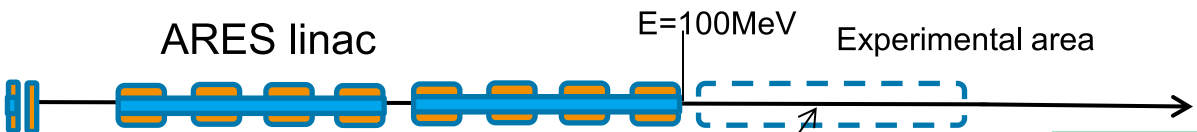
SINBAD overview –
Cfr: U. Dorda et al. "SINBAD – The accelerator R&D facility under construction at DESY", NIM A ***829****, p. 233-236 (2016).*

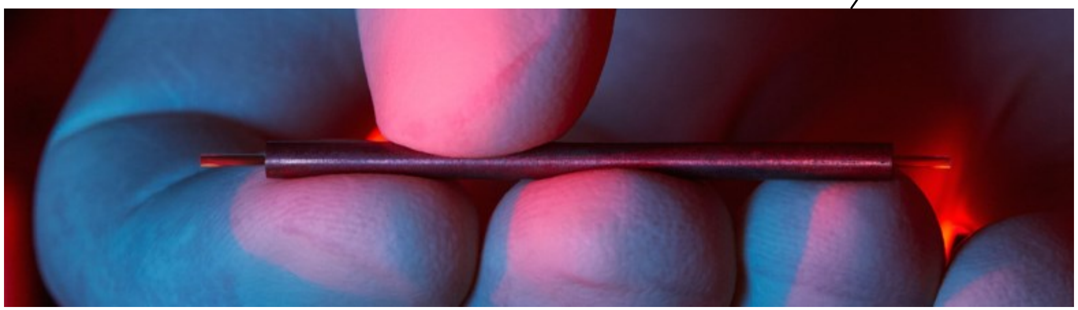




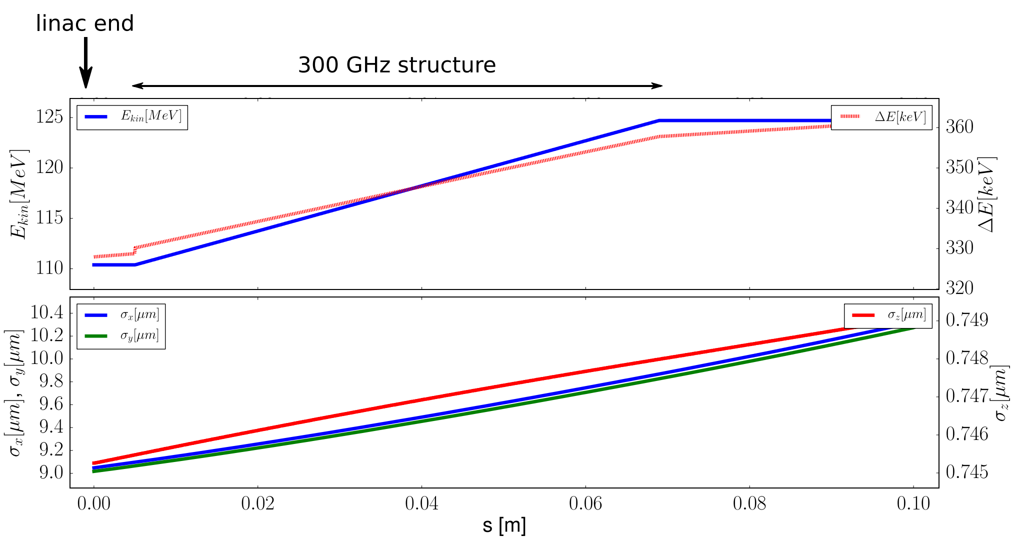
- Temporary experimental area
- Space for future possible energy upgrade

Science at ARES (1/3): AXSIS @ ARES





Possible injection of ARES e-bunches in AXSIS-like THz booster



Simulation by Ulrich Dorda

Acceleration in THz laser driven dielectric structures

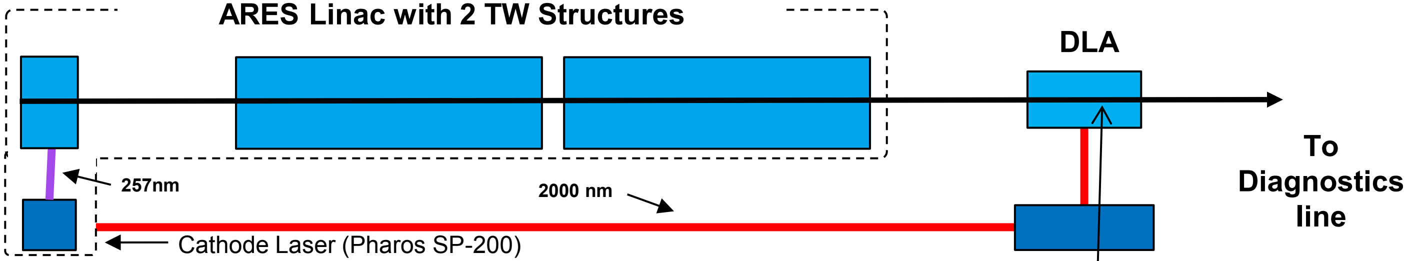
E. Nanni et al. Nat. Comm. 6 (2015) 8486.

Typical THz linac parameters:

- Aperture-size: ~1mm
- Length: ~10 cm
- Period of accelerating field : 3ps
- Gradient ~ hundreds MV/m

Injected beam parameters	
FWHM [fs]	4
ΔE/E [%]	0.3
$\sigma_{x,y}$ [mm]	0.009
$n\varepsilon_{x,y}$ [μm]	0.05

Science at ARES (2/3): Dielectric Laser Acceleration (DLA)



- Laser-illuminated dual layer grating (DLA)
  - Dielectric structure (SiO_2, Si, etc.)

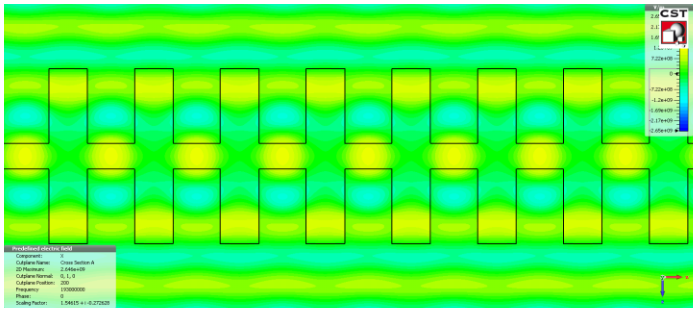
Typical DLA sample:

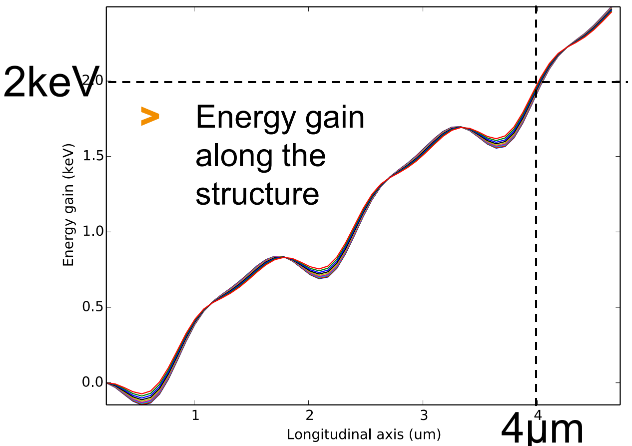
- Aperture-size: ~0.6um
- Length: ~1 mm
- Period of accelerating field: 6.7fs
- Gradient ~hundred MV/m

- Possible working point for producing ultra-short e-bunch probe by velocity bunching compression in the linac

Parameter @ IP (15.86 m)	Value
Charge [pC]	0.5
Bunch Length [fs,rms]	1.53 (0.23 * λ)
E [MeV]	94.1
$\sigma_{x,y}$ [μm]	4.5
$n\varepsilon_{x,y}$ [μm]	0.063

- Longitudinal electric field inside the structure





- Energy gain along the structure

Study and Simulations by F. Mayet and W. Kuropka

Science at ARES (3/3): External injection in LWFA (Laser driven Wake-Field Acceleration)

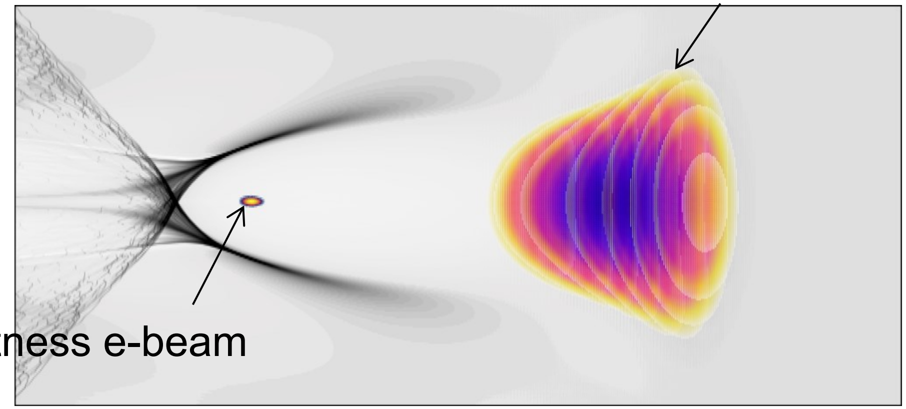


Image courtesy: A. Martinez de la Ossa

Working principle:

- Intense laser-pulse pushes away electrons by its ponderomotive force and creates electron-depleted region
- Strong electrostatic fields pull back
- electrons on axis
- Electrons oscillate and create co-propagating wake-field

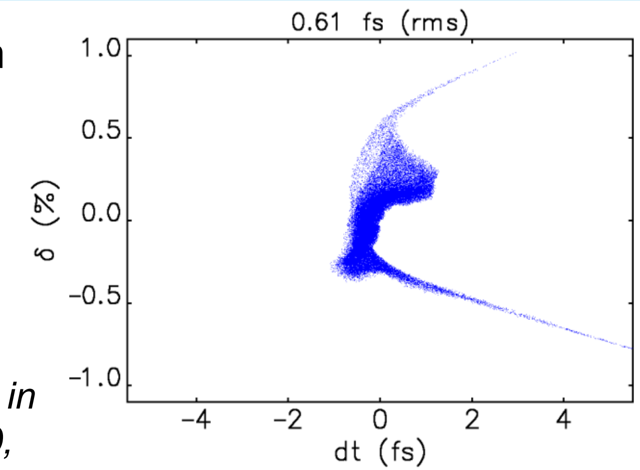
Typical parameters for LWFA at SINBAD:

- Matched transverse beam size ≤ 1μm
- Acceleration Length: from few cm up to tens of cm
- Period of accelerating field (10^{16}cm^{-3} plasma density): 1 ps
- Gradient ~ tens GeV/m

Cfr: R. Assmann, J. Grebenyuk, TUOBB01, Proceedings of IPAC2014.

Example of Ultra-Short Beam with low (<10fs) RMS arrival time jitter for injection in LWFA

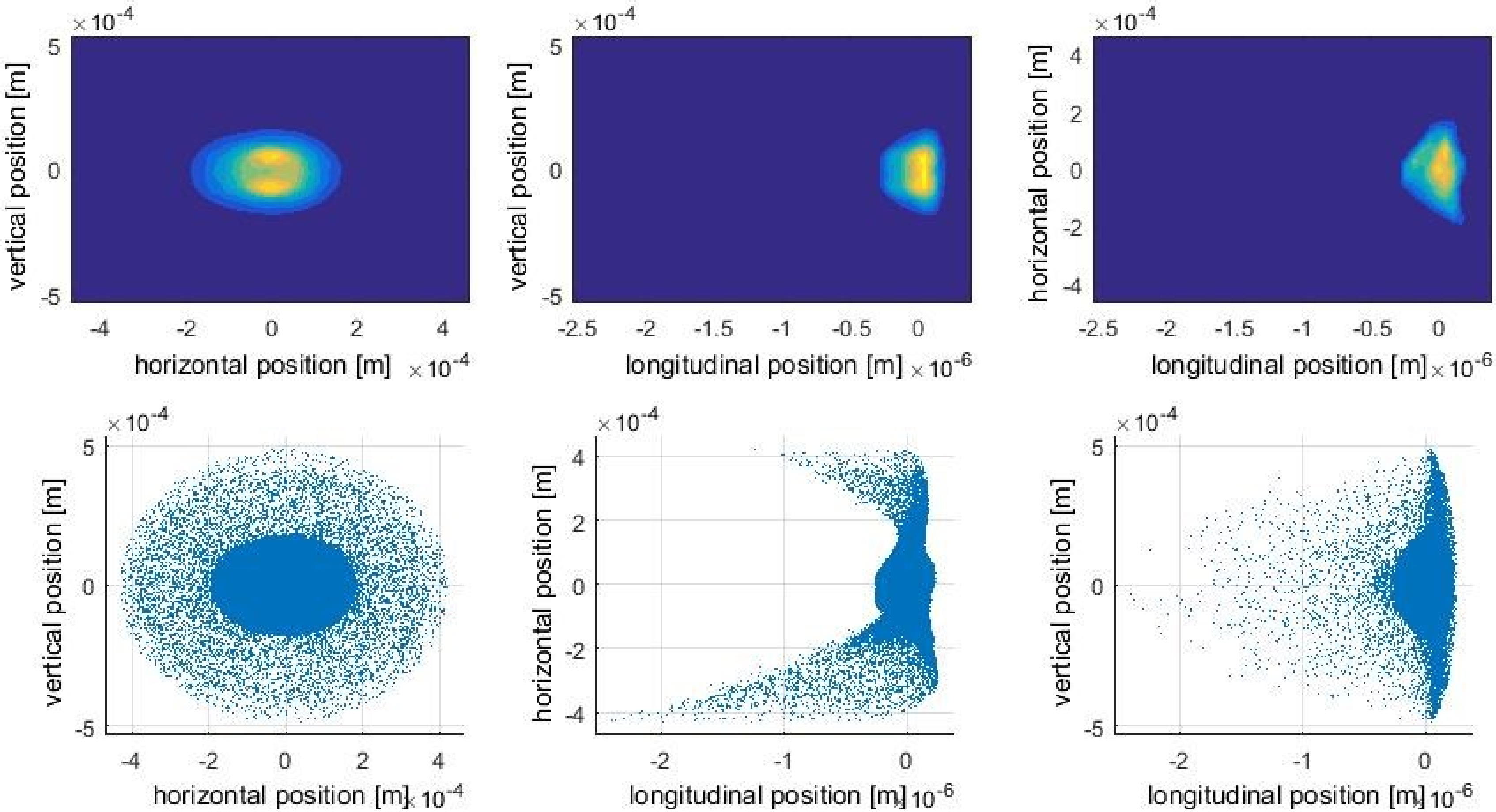
Cfr: J. Zhu et al. "Sub-fs bunch generation with sub-10-fs bunch arrival time jitter via bunch slicing in a magnetic chicane", PRSTAB ***19****, 054401 (2016)*



DESY

Production and measurement of ultra-short probe for LWPA

Beam shape at the TDS



Q=2.7pC
Energy = 100MeV
Transverse Normalized Emittance = 0.2 mm*mrad
σt=0.461fs

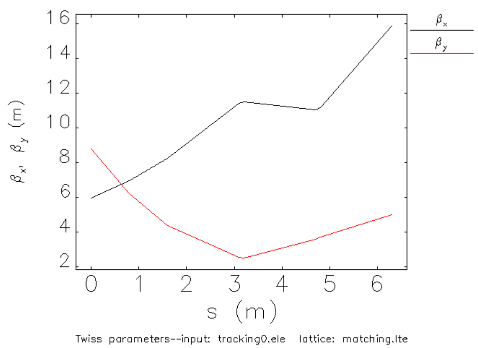
Beam production simulated by J. Zhu

Production and measurement of ultra-short probe for LWPA

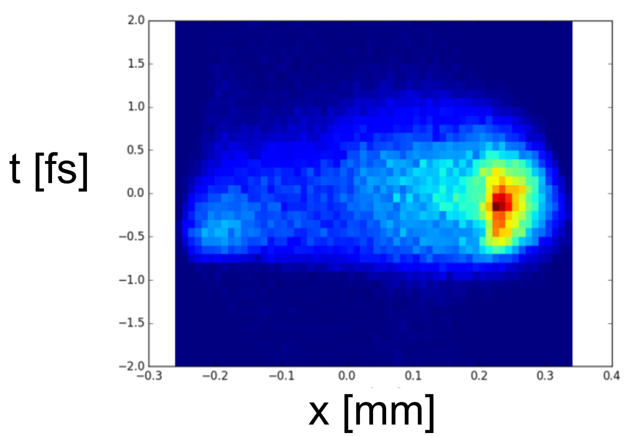
Beam parameters at the TDS

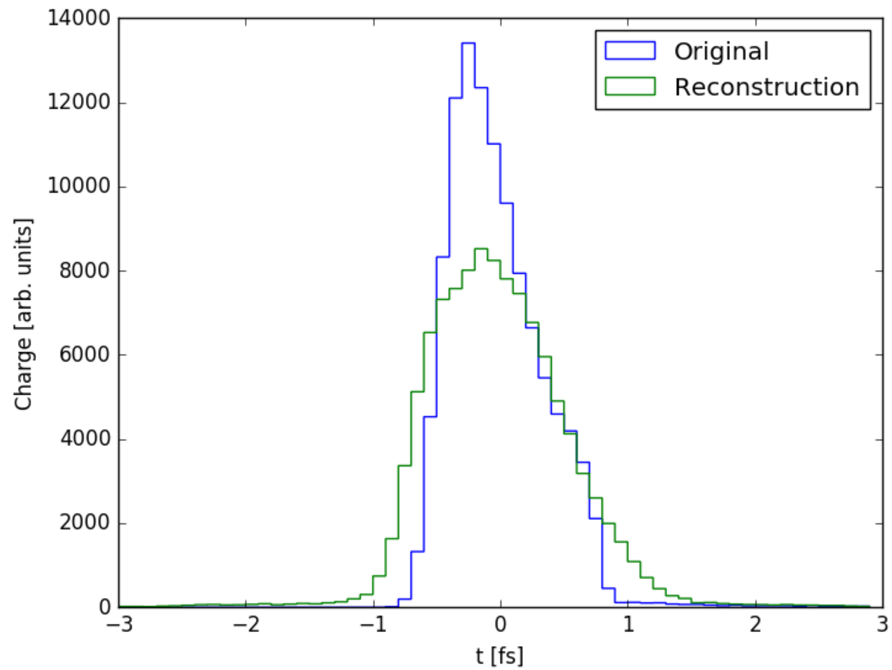
V = 40MV
β(s0) = 6m (as from bunch compression)
Δφ = π/2

Beam optics between TDS and screen



Simulated Measured Streaked Beam @ Screen





Longitudinal Resolution = 0.42 fs

- Calibration done at reduced voltage
- Jitter effects non included
- Code used: Elegant (Space Charge OFF)

Study and Simulations by D. Marx

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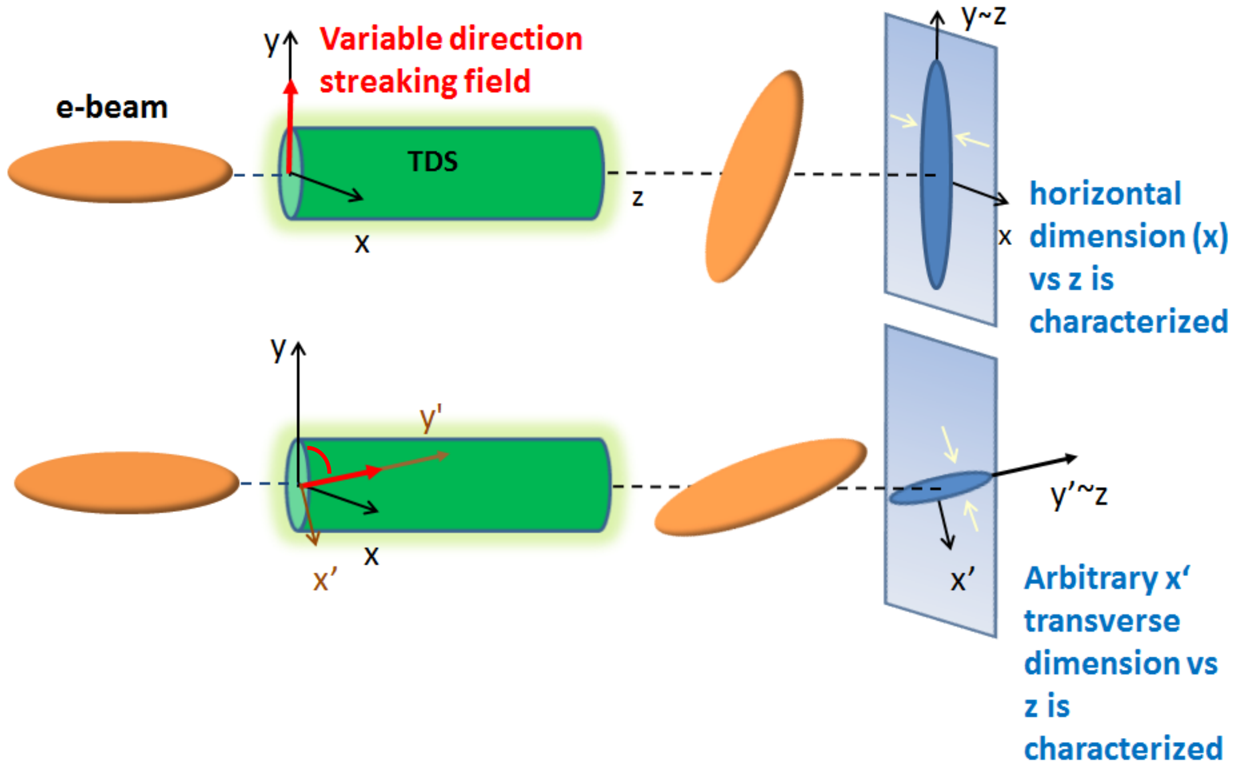
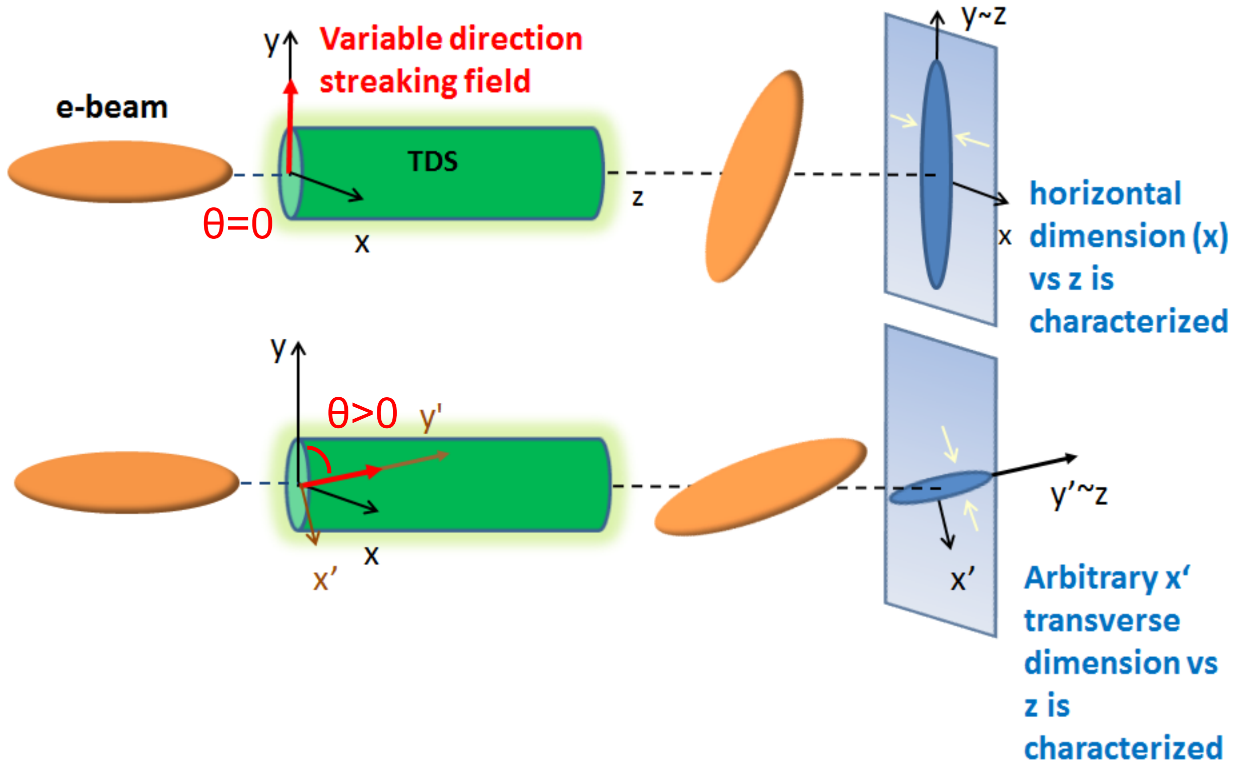
Variable polarization TDS – Novel beam diagnostics opportunities



Exciting new opportunities for e-bunch characterization e.g.:

- slice emittance measurement on different planes,
- **3D charge reconstruction (described here)**
- 6D beam phase space reconstruction

Variable polarization TDS – Novel beam diagnostics opportunities



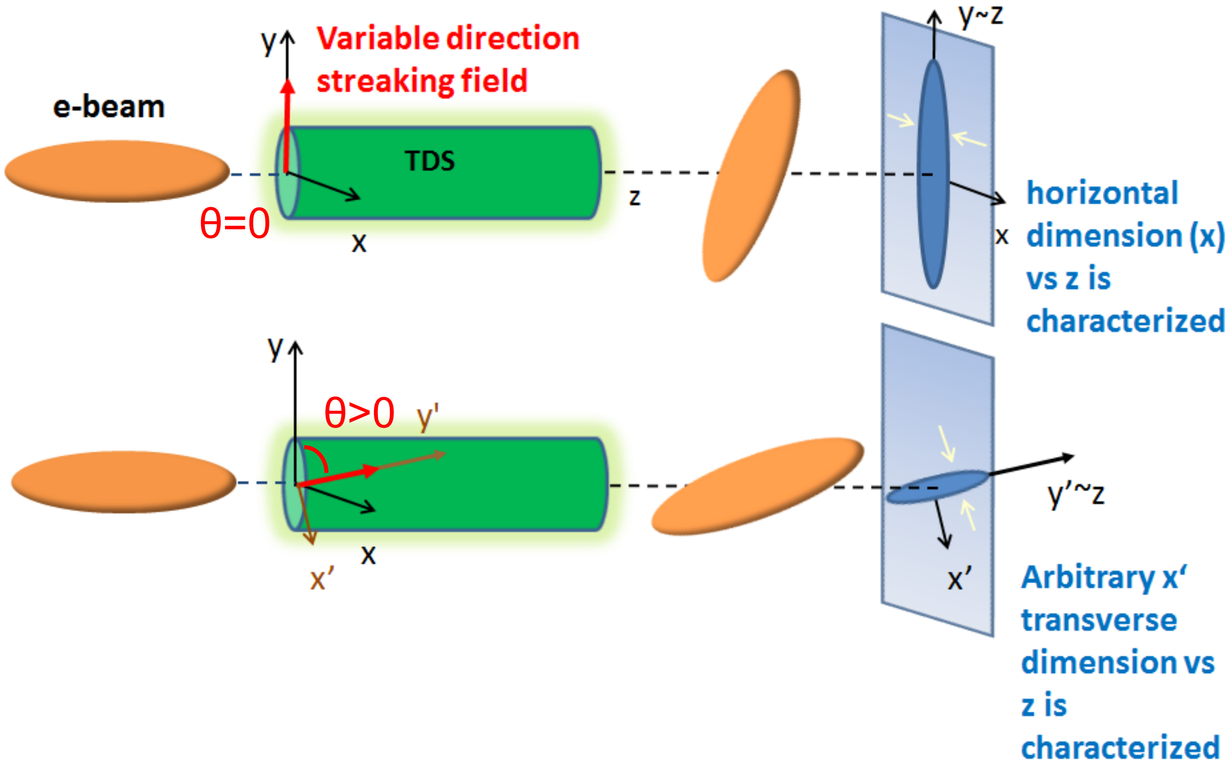
Exciting new opportunities for e-bunch characterization e.g.:

- slice emittance measurement on different planes,
- **3D charge reconstruction (described here)**
- 6D beam phase space reconstruction

Definition of Reference Systems:

- x-y defines the e-bunch transverse reference system
- y' is the transverse axis parallel to the direction of the streaking
- x' is perpendicular to y' in the transverse plane
- θ is the angle between y and y'.

Reconstruction of 3D Charge Distribution



"Reconstruction of the 3D Charge Distribution of an Electron Bunch Using a Variable-Polarization Transverse Deflecting Structure (TDS)"
D. Marx et al.

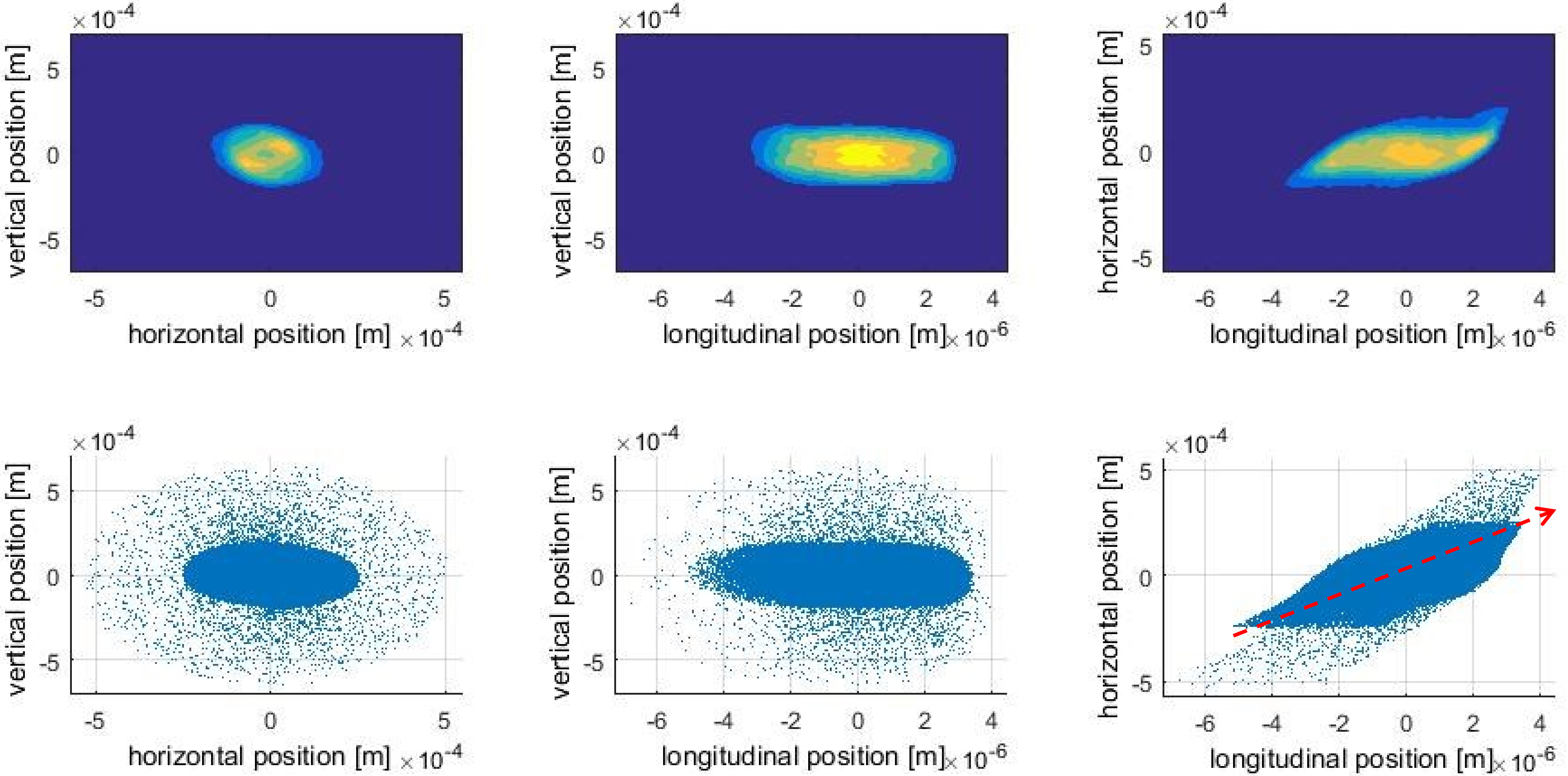
Article in preparation.
Poster at IPAC17.

Measurement „Recipe"

- 4 streaking directions of the TDS are used ($\theta=0$, $\theta=\pi/4$, $\theta=\pi/2$, $\theta=3/4\pi$).
- The beam on the screen is divided into longitudinal slices.
- The 2D charge distribution of each slice at the screen is reconstructed by using a tomographic algorithm (e.g. Back-Projections, SART).
- The transverse profiles of the slices are combined to get a 3D charge distribution.

Reconstruction of 3D Charge Distribution

Input beam used for test simulations at the TDS

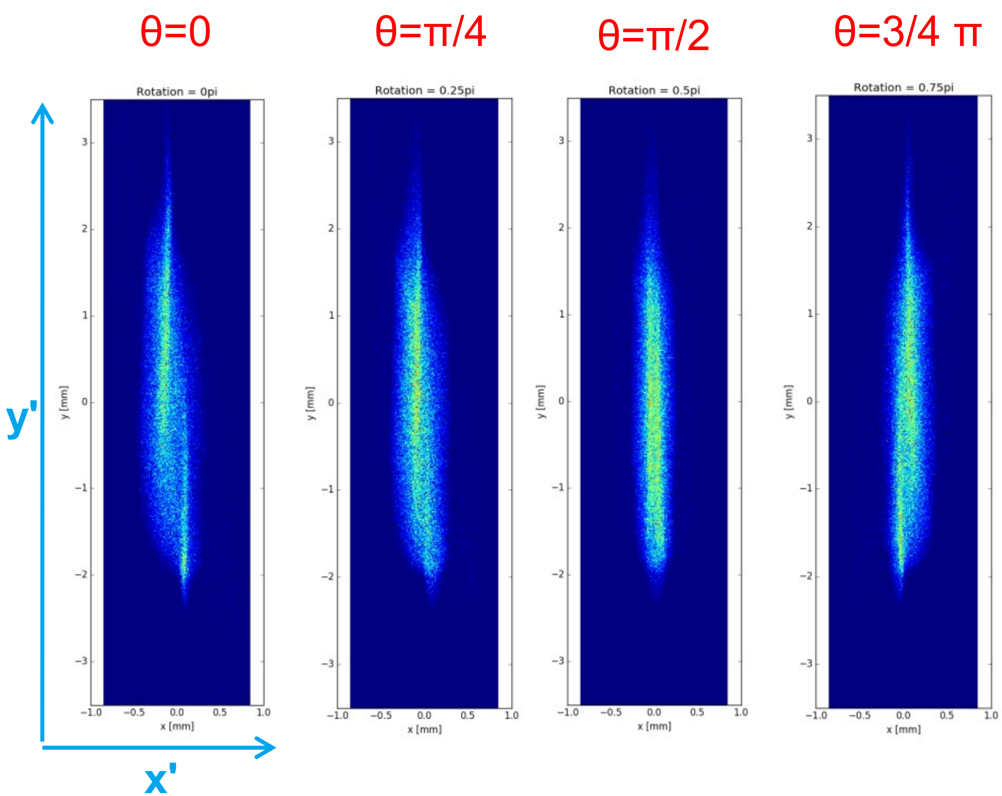


Example of correlation x-z that we wish to detect

Input beam generated at the SINBAD-ARES linac via magnetic compression
Simulations by J. Zhu

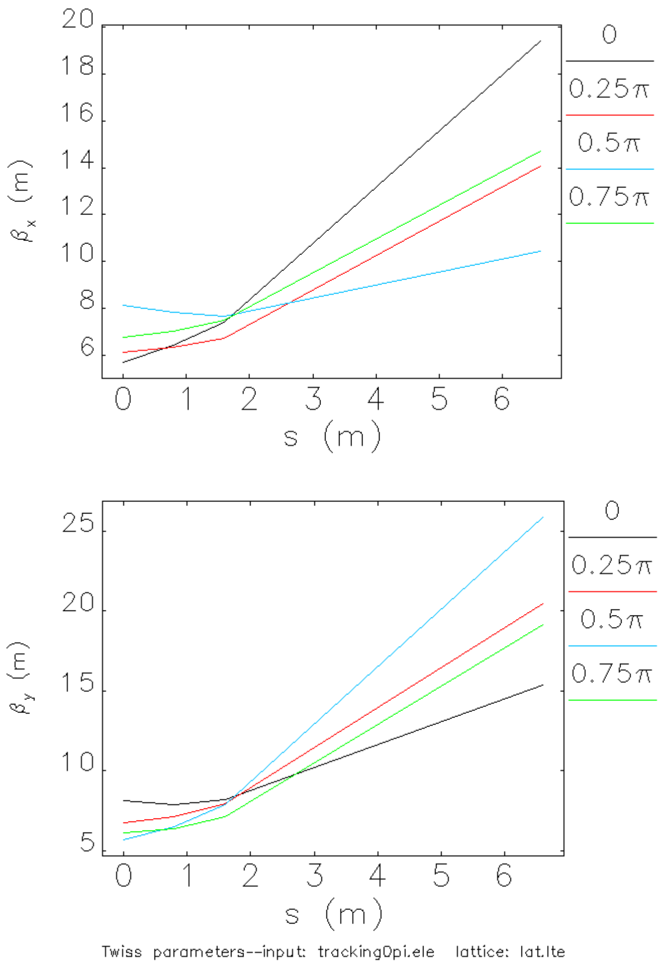
Reconstruction of 3D Charge Distribution

Image at the screen for different streaking directions



Simulations done by using ELEGANT (Space Charge OFF).

Beam optics between TDS and screen

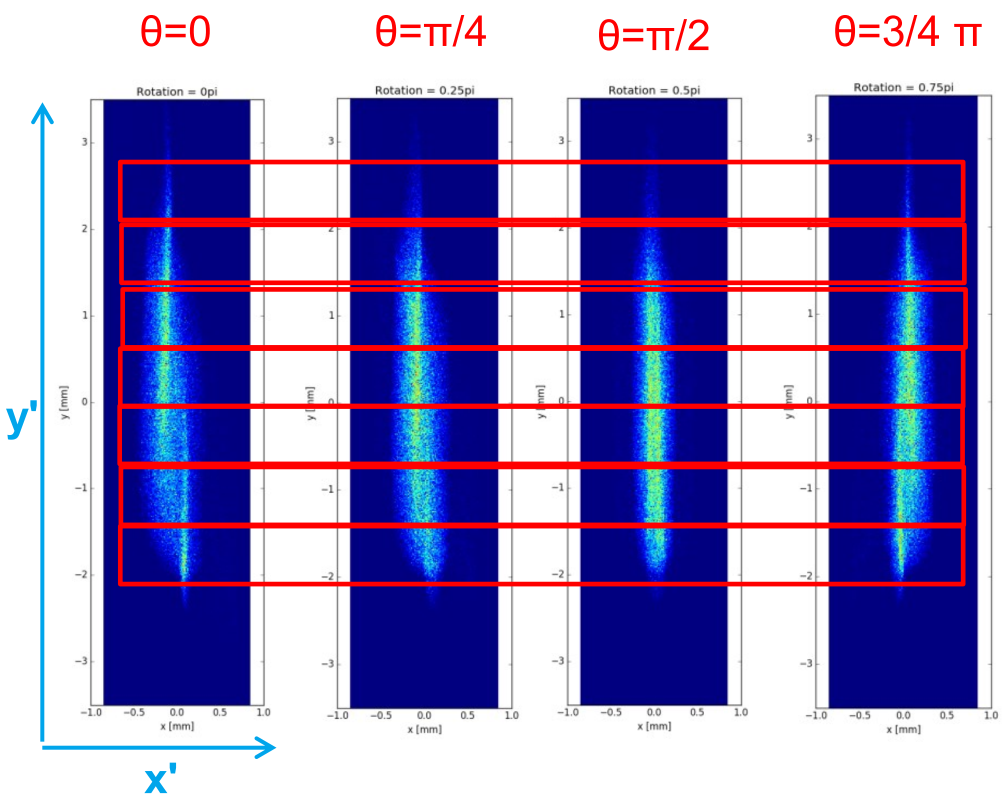


Study and Simulations by D. Marx

Reconstruction of 3D Charge Distribution

Article in preparation

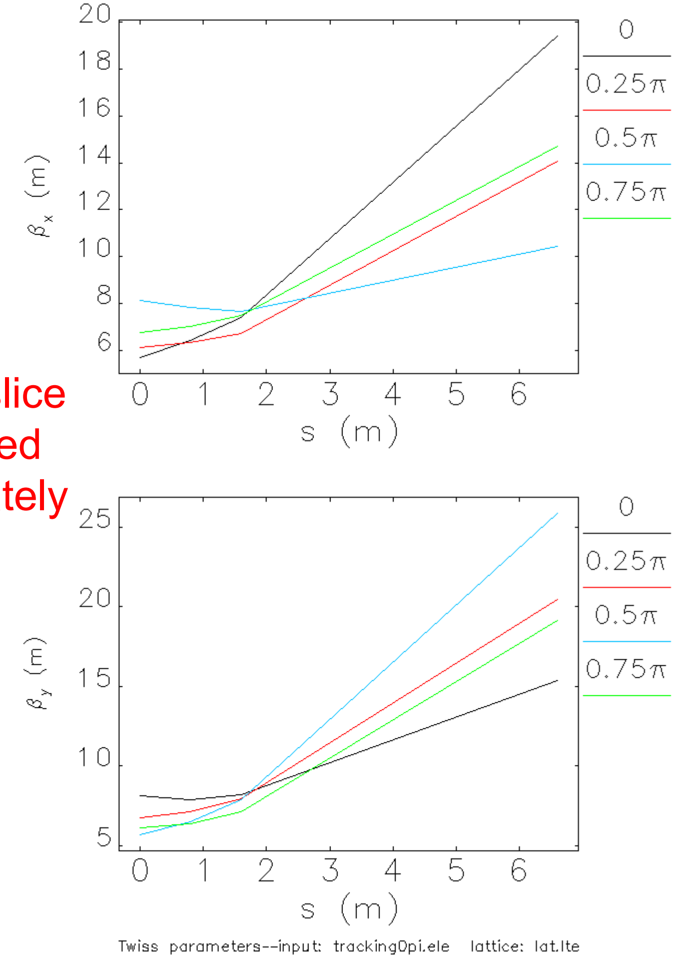
Image at the screen for different streaking directions



Simulations done by using ELEGANT (Space Charge OFF).

Beam optics between TDS and screen

Each slice analyzed separately

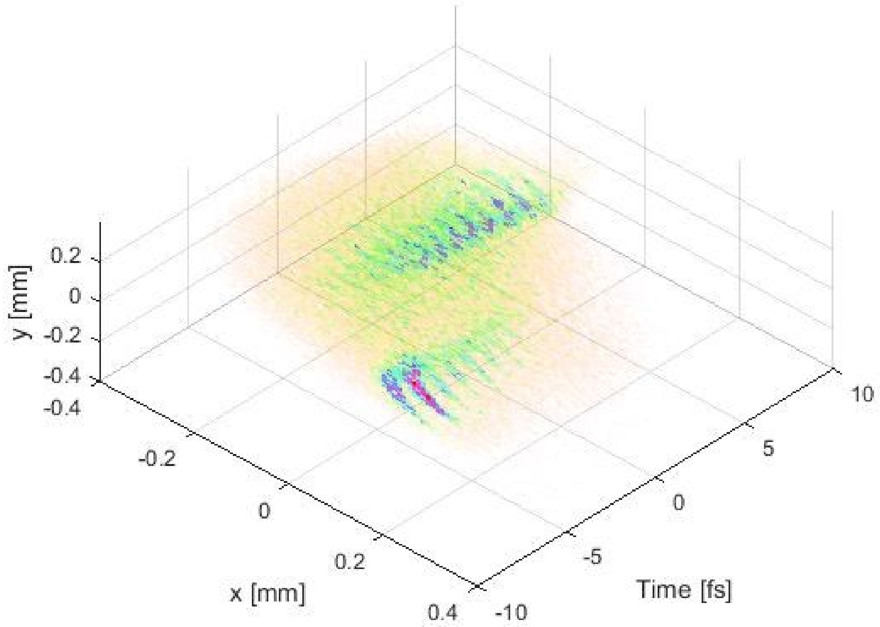


Study and Simulations by D. Marx

DESY

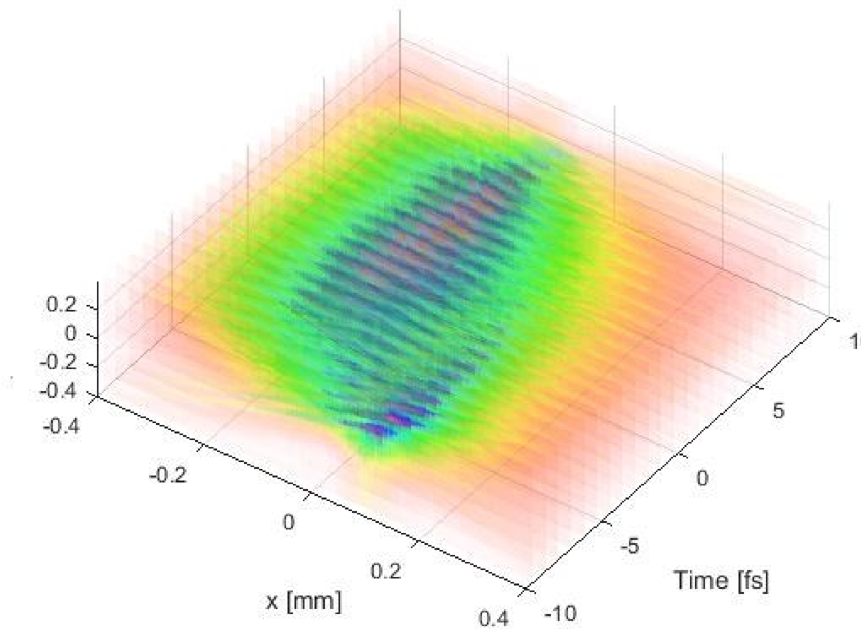
Reconstruction of 3D Charge Distribution

Article in preparation



Original beam at the screen location

The slices are finally combined in a 3D plot



Reconstructed beam at the screen location

Study and Simulations by D. Marx

Conclusion & Outlook

- We have introduced the **state of the art** of longitudinal phase space characterization by using an **X-band TDS**. We have highlighted as the **recent progresses** in the fields of high gradient X-band cavity design (made at **CERN**) and manufacture (made at **PSI**) allows us to aim for a **new generation of TDS systems** with more extended capabilities for **3D characterization** of the beam.
- We have summarized the **potential applications** of X-band TDS systems at **DESY** for:
  - measurement of the energy spread induced by FEL lasing (**FLASH2**)
  - characterization of driver and witness electron beams in PWFA (**FLASHForward**)
  - characterization of ultra-short (fs / sub-fs) electron bunches for injection on novel high gradient acceleration techniques (**SINBAD**)
- We have described a **novel measurement technique** for **3D e-bunch charge reconstruction** currently under study at **DESY** which makes special use of the variable polarization TDS.

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Thank you for the attention!