Temporal Streaking of Electron Beams in any Transverse Plane with Femtosecond Resolution

PolariX-TDS Project

10th International Beam Instrumentation Conference – IBIC2021 (Pohang, Korea)

Pau González Caminal (on behalf of the PolariX-TDS Collaboration)

FLASHForward | Research Group for Plasma Wakefield Accelerators

Deutsches Elektronen Synchrotron DESY, Accelerator Division, Hamburg, Germany

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES | Universität Hamburg DER FORSCHUNG | DER LEHRE | DER BILDUNG | PAUL SCHERRER INSTITUT PSI | CERN | DESY.

Credits and contributions

- **DESY**

  R. Assmann, B. Beutner, J. Branlard, ***F. Burkart***[§], F. Christie, B. Conrad, M.K. Czwalinna, ***R. D'Arcy***[§], W. Decking, U. Dorda, M. Foese, P. González Caminal, J. Herrmann, M. Hoffmann, M. Hüning, S.M. Jaster-Merz, R. Jonas, *K. Klose*, O. Krebs, G. Kube, S. Lederer, F. Ludwig, K. Ludwig, B. Marchetti, D. Marx, D. Meissner, J. Osterhoff, I. Pepperkorn, S. Pfeiffer, F. Poblotzki, M. Reukauff, J. Roensch-Schulenberg, J. Rothenburg, G. Tews, H. Schlarb, M. Scholz, ***S. Schreiber***[§], ***T. Vinatier***[*], ***M. Vogt***[§], A. de Z. Wagner, T. Wilksen, S. Wesch, K. Wittenburg, J. Zemella

- **PSI**

  M. Bopp, ***P. Craievich***[*§], H.-H. Braun, E. Citterio, R. Fortunati, R. Ganter, T. Kleeb, F. Marcellini, M. Pedrozzi, E. Prat, S. Reiche, K. Rolli, R. Sieber, R. Zennaro

- **CERN**

  N. Catalan Lasheras, ***A. Grudiev***[*], G. McMonagle, W. L. Millar, S. Pitman, V. del Pozo Romano, K.T. Szypula, W. Wuensch

***** Institution coordination***
§ Research facility coordination

Scientific motivation for a fs-resolution, polarisable-streak TDS

- Diagnose both transverse and longitudinal slice properties for machine optimisation in e.g. FELs

Transverse Deflection Structure (TDS)

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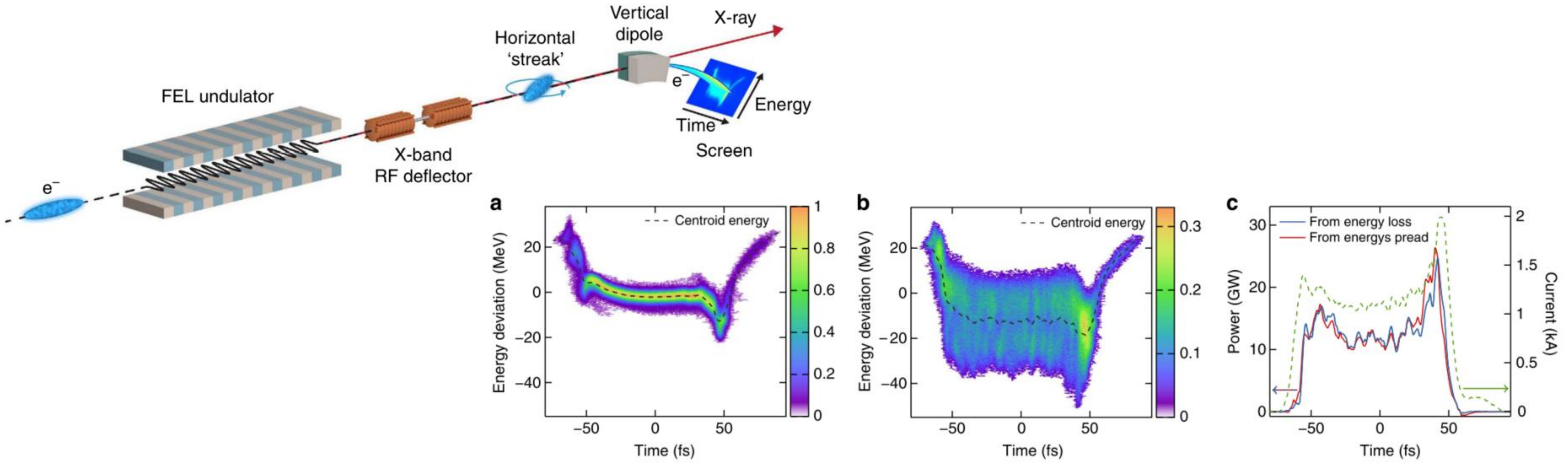
- Femtosecond-level temporal resolution are required for optimisation of ultra-short bunches

Transverse Deflection Structure (TDS)

High-frequency (X-band) range



C. Behrens et al., Nature Communications, vol. 5, p. 3762, 2014.

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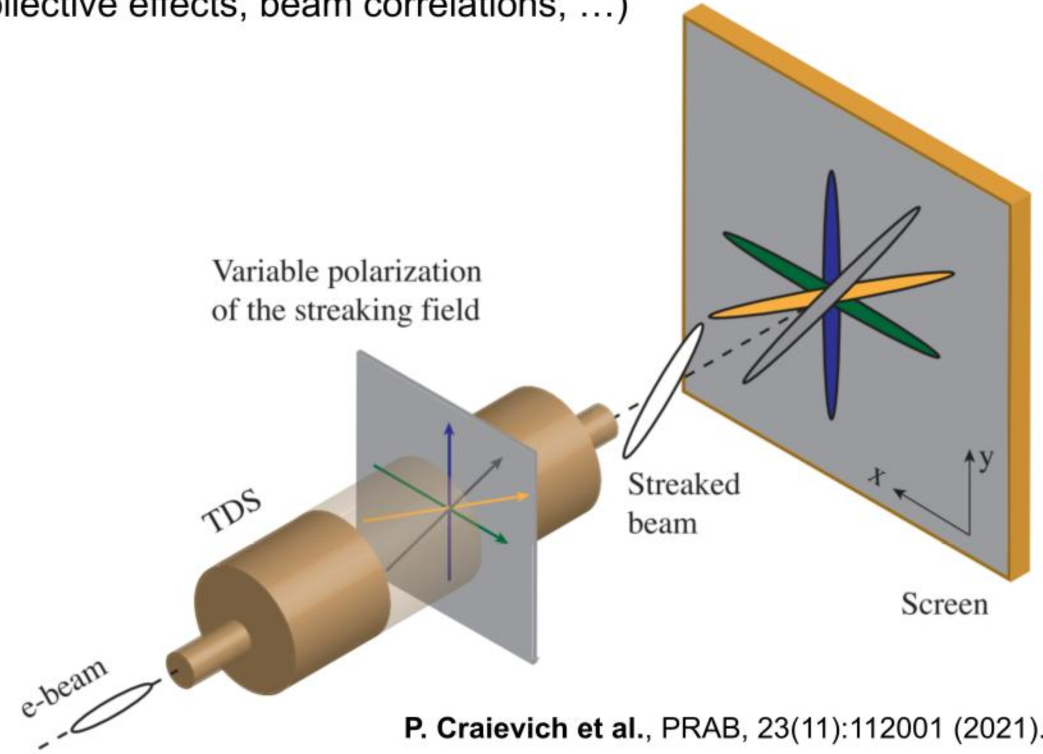
Variable polarisation streaking



P. Craievich et al., PRAB, 23(11):112001 (2021).

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- The ~kT/m focusing gradients inherent to novel high-gradient accelerator concepts require high-quality, axially-symmetric beams

Transverse Deflection Structure (TDS)

High-frequency (X-band) range

Variable polarisation streaking

Hosing instability

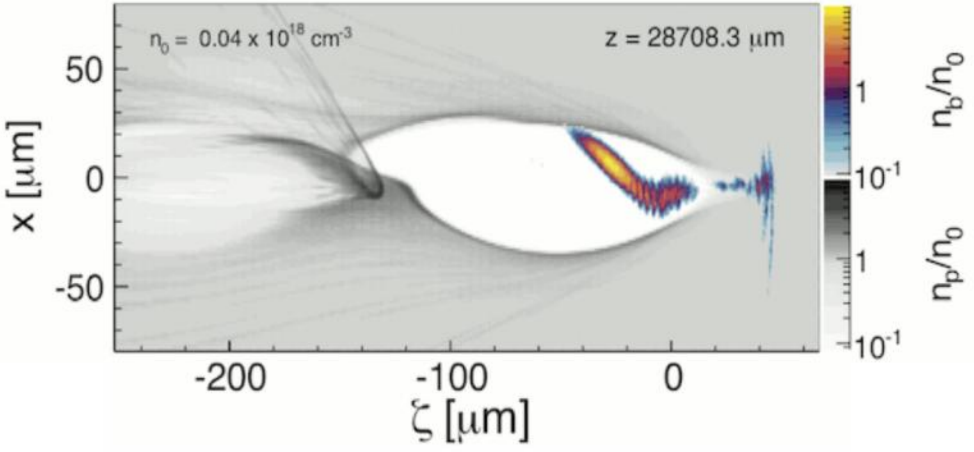

Figure courtesy of **A. Martínez de la Ossa** (DESY).

PolariX-TDS Collaboration Background

- Design of compact high-power RF components at X-band in 2016 by Alexej Grudiev [1]
- High-precision tuning-free assembly procedure developed at PSI [2, 3]
- New diagnostics requirements at four facilities:
  - **FLASHForward** (beamline at FLASH, DESY): fs-longitudinal diagnostics of driver/witness beams used in plasma-wakefield acceleration (PWFA)
  - **ARES-SINBAD** (facility at DESY): sub-fs longitudinal characterisation of ultra-short electron bunches
  - **FLASH2** (beamline at FLASH, DESY): online longitudinal measurement with fs resolution of electron bunches for optimising FEL process and UV/soft X-ray photon-pulse reconstruction
  - **ATHOS** (beamline at SwissFEL, PSI): online longitudinal measurement with sub-fs resolution of electron bunches for optimising FEL process and soft X-ray photon-pulse reconstruction

[1] **A. Grudiev**, CLIC-Note No. 1067 (CERN, Geneva, Switzerland, 2016).

[2] **U. Ellenberger, et al.**, 11th International Conference on Synchrotron Radiation Instrumentation 425, 072005 (2013).

[3] **R. Zennaro, et al.**, in Proceedings of the 27th International Linear Accelerator Conference, pp. 333–335.

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PolariX-TDS Collaboration (2017)

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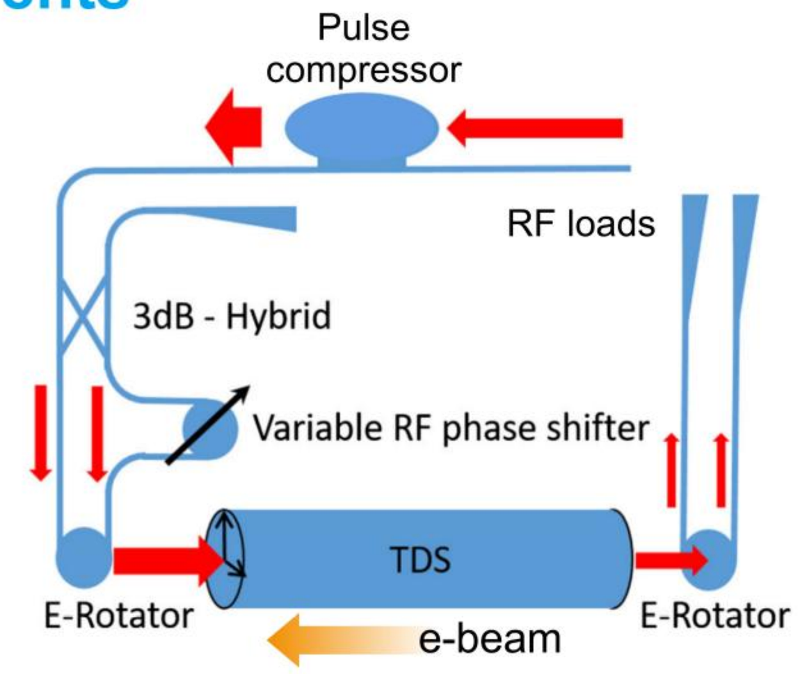

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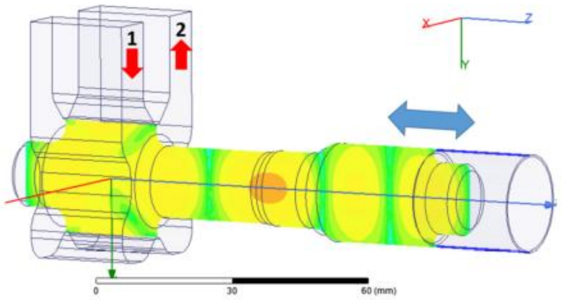

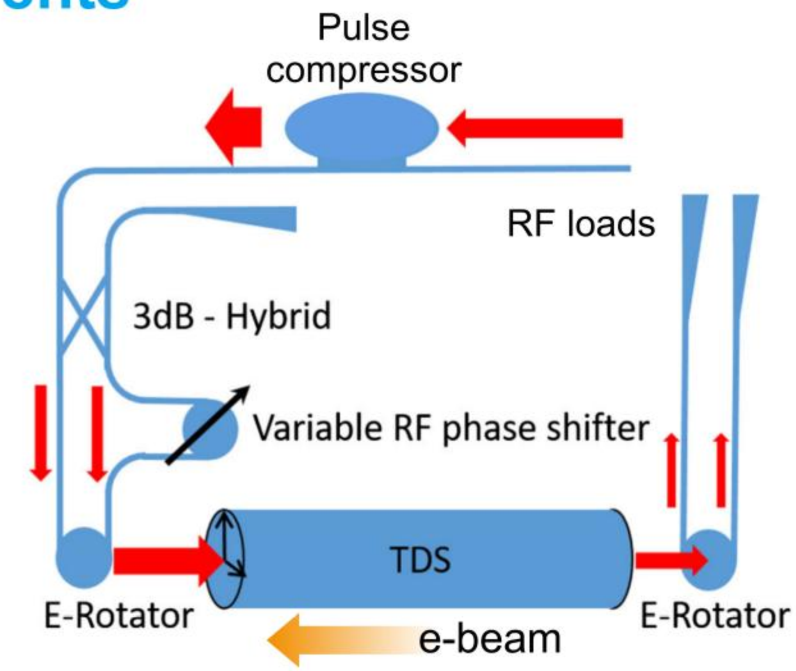

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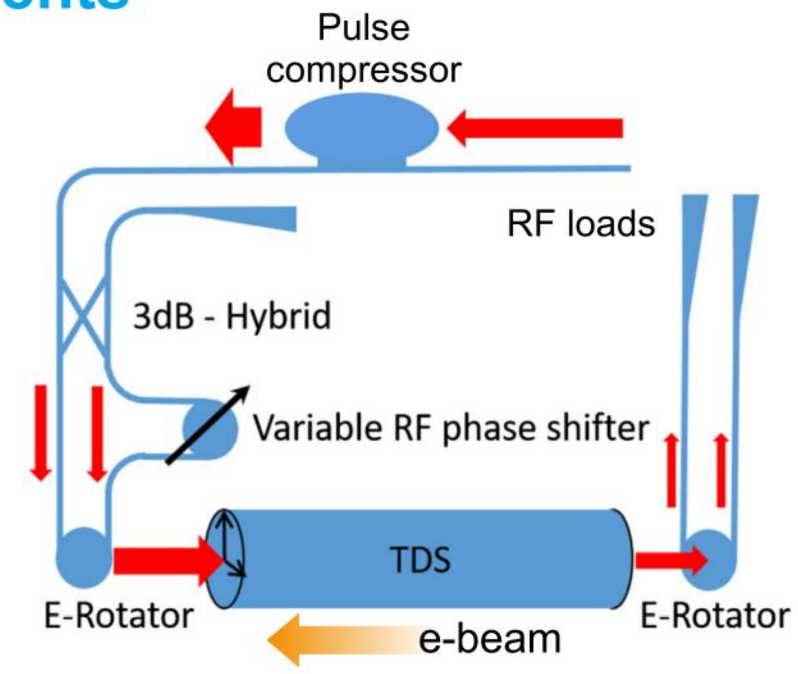

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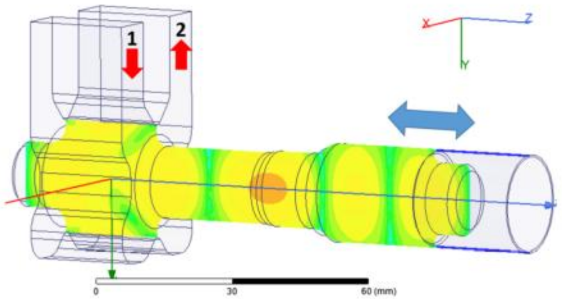

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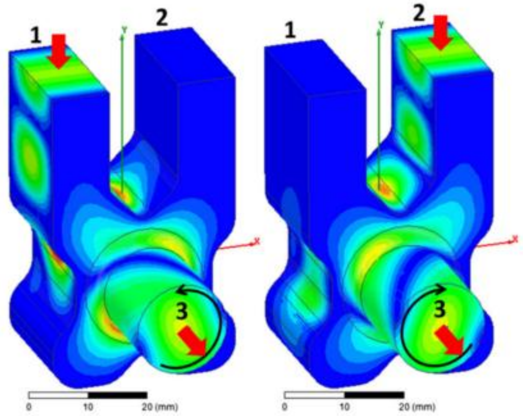

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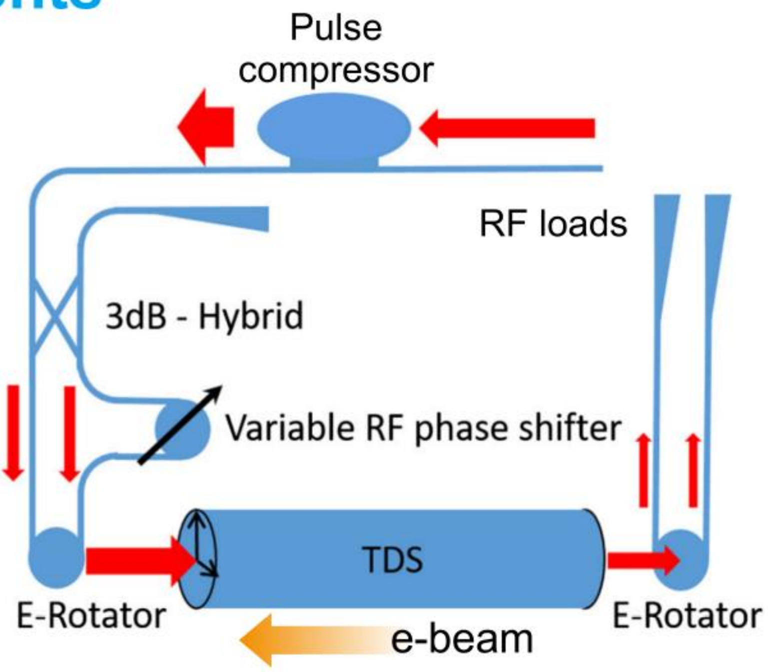

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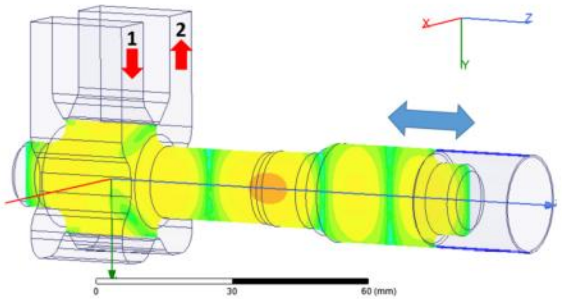

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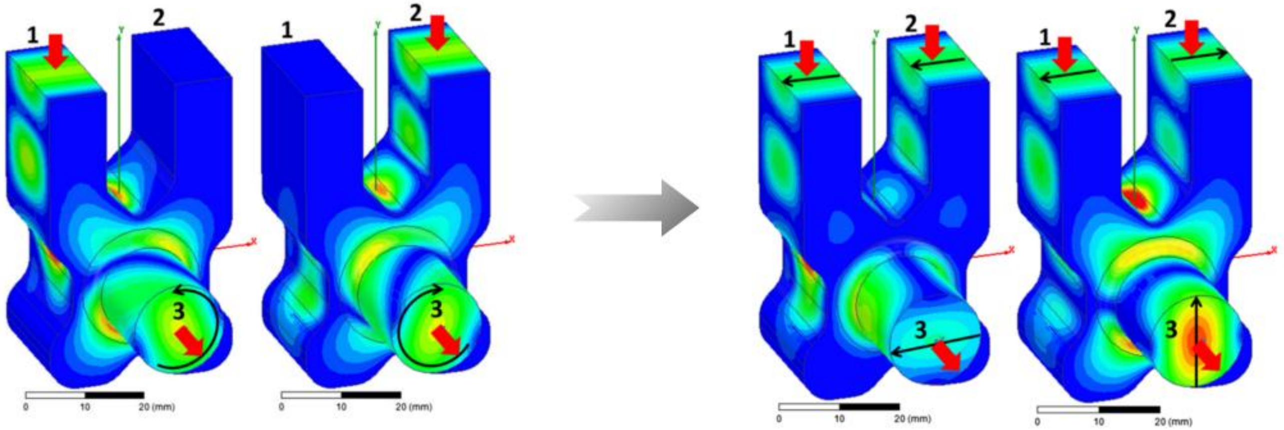

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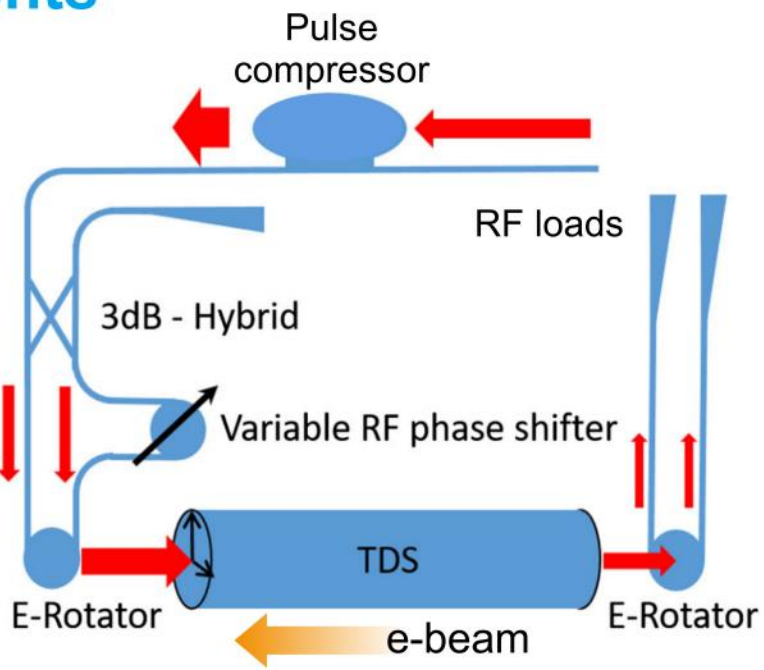

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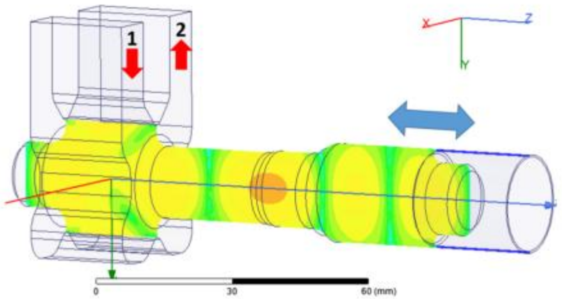

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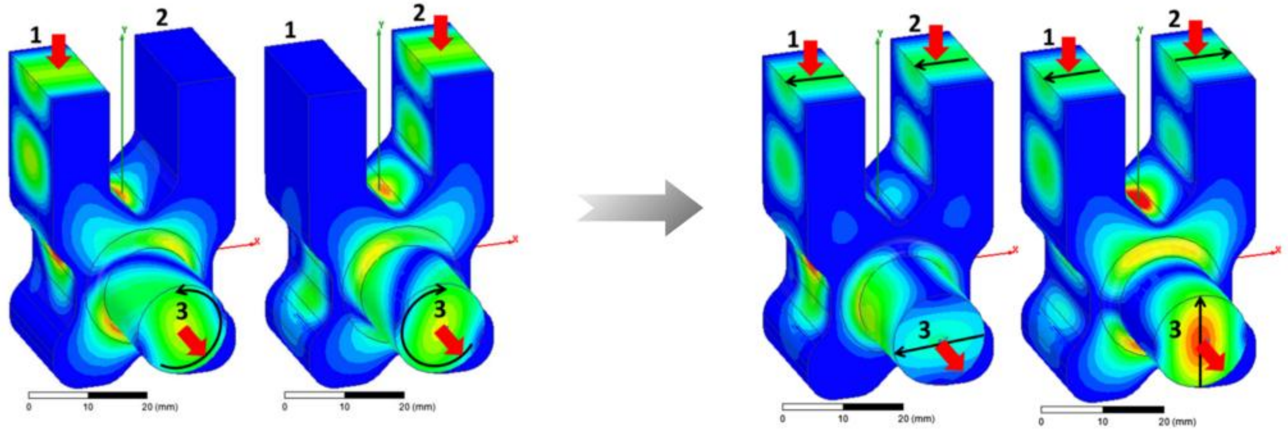
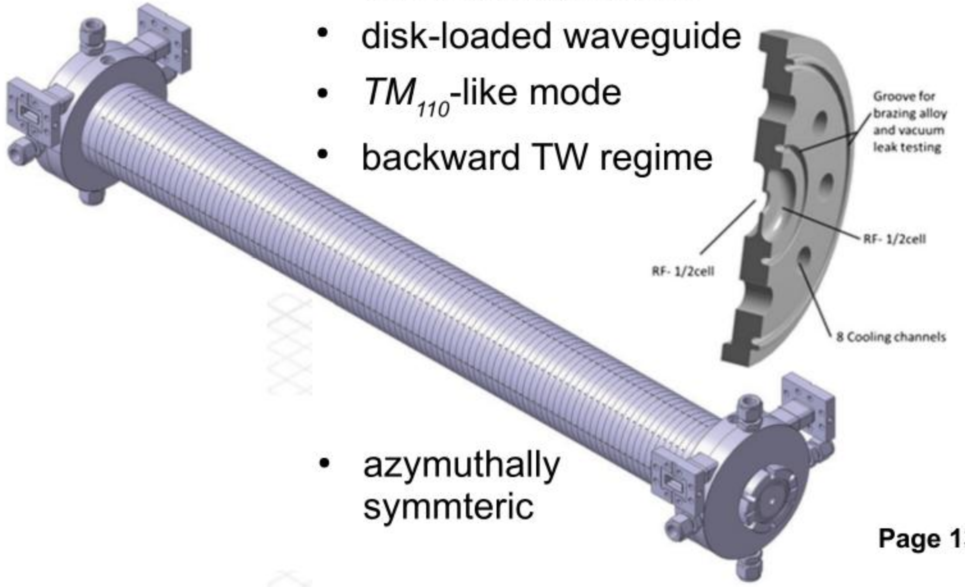


> Transverse deflection structure [2]
- constant impedance
- disk-loaded waveguide
- TM_{110}-like mode
- backward TW regime
- azymuthally symmteric



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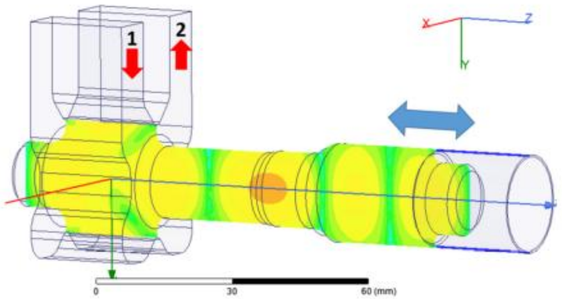

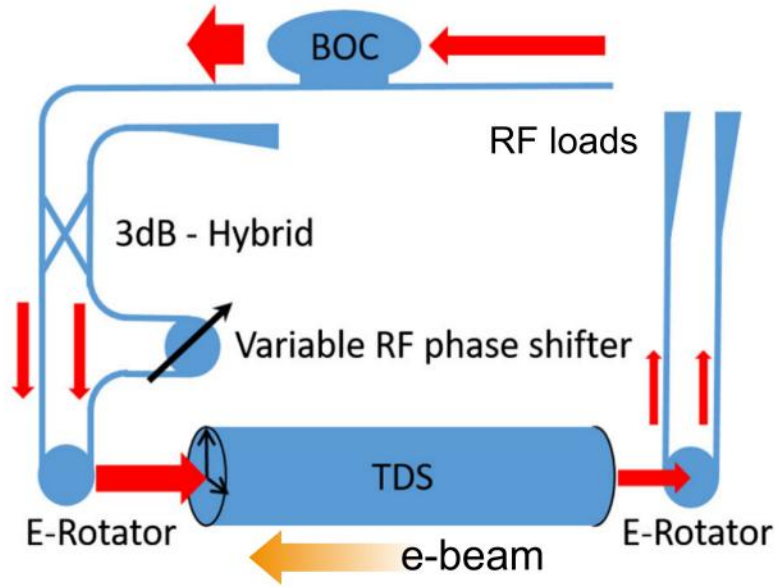

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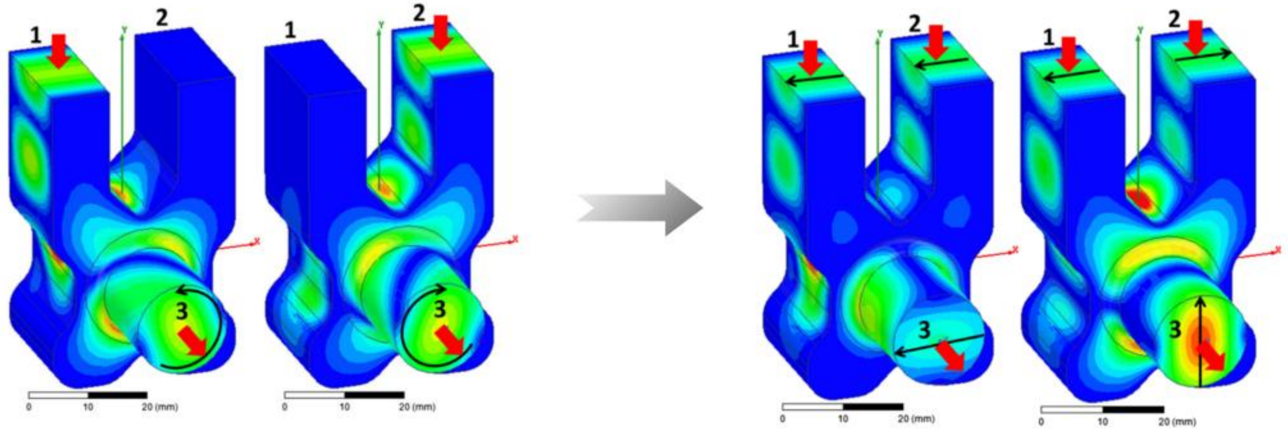
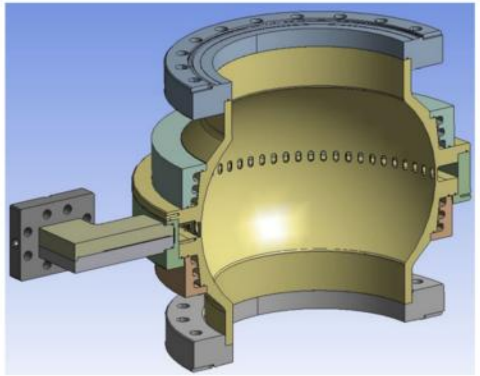


> X-band barrel open cavity (XBOC) [2, 3]



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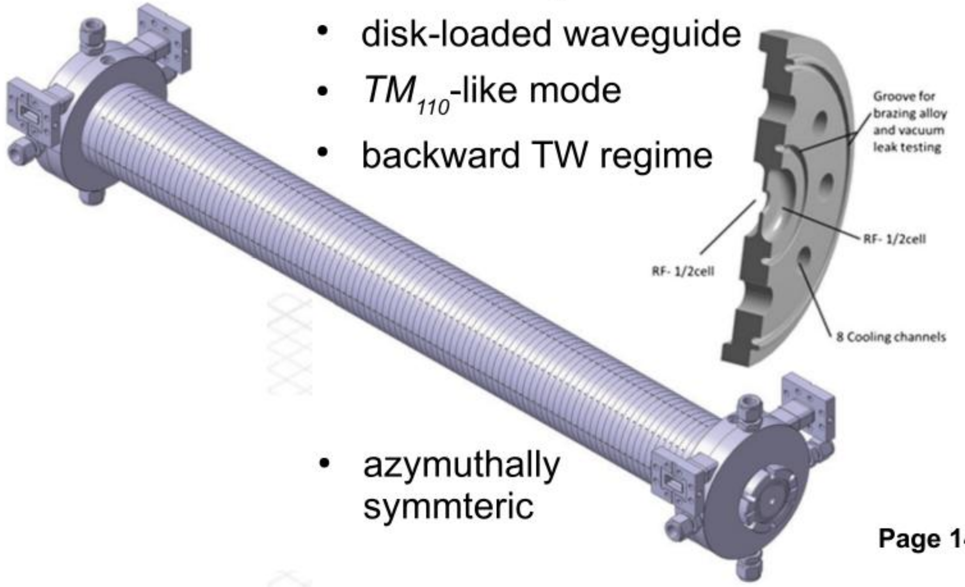

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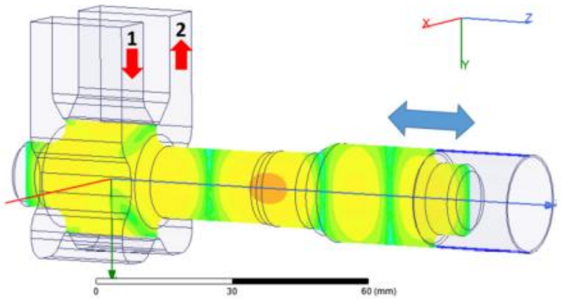

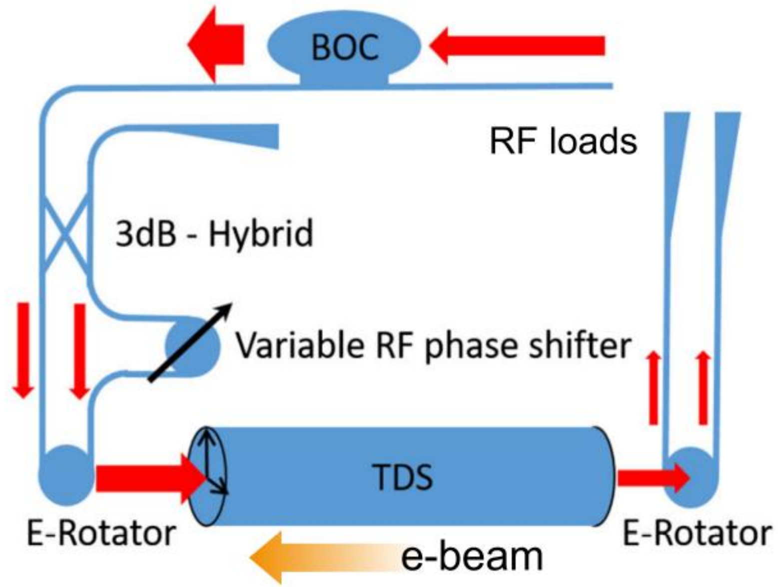

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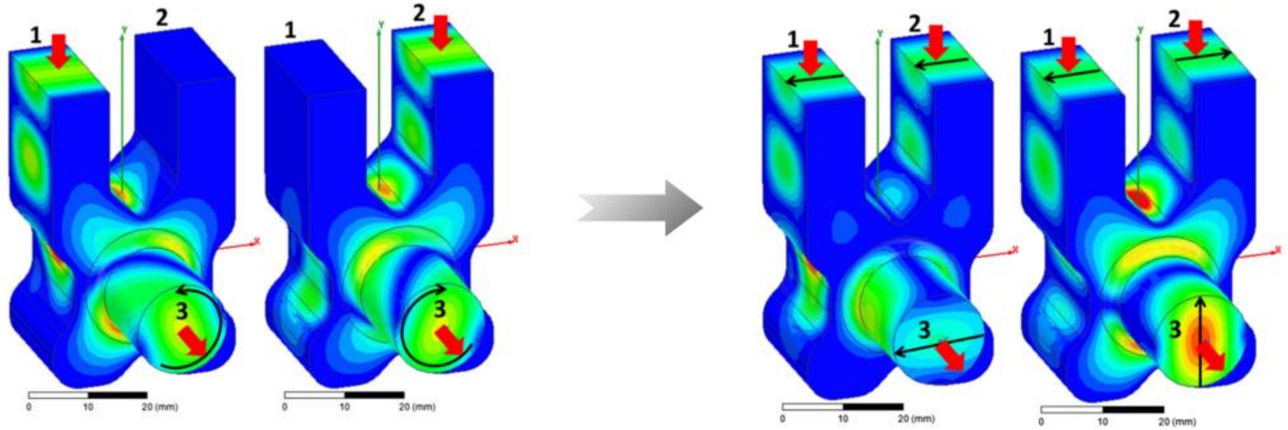

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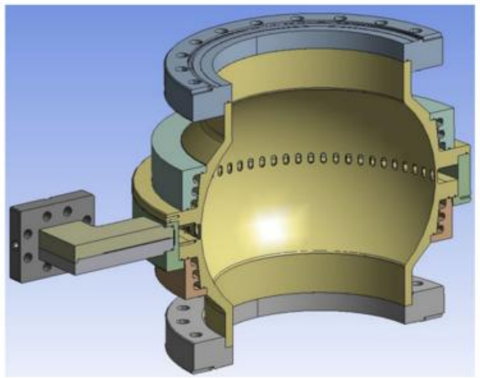

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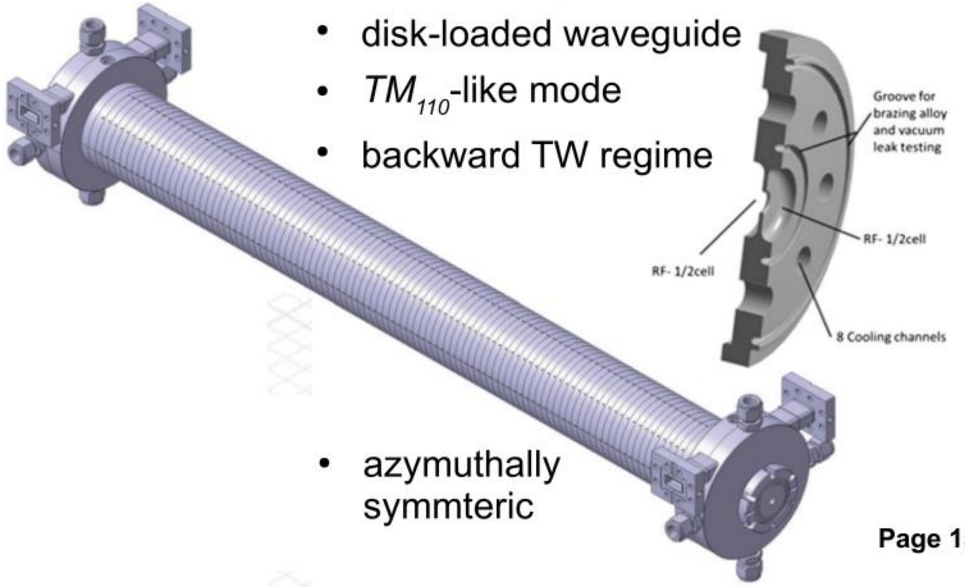

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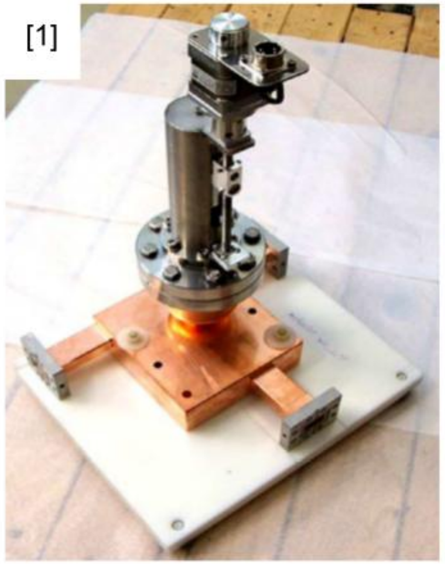

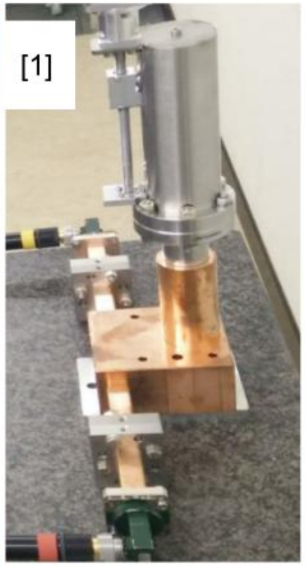

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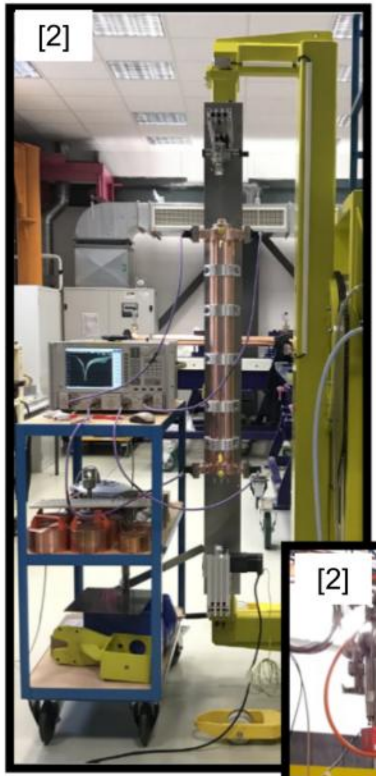
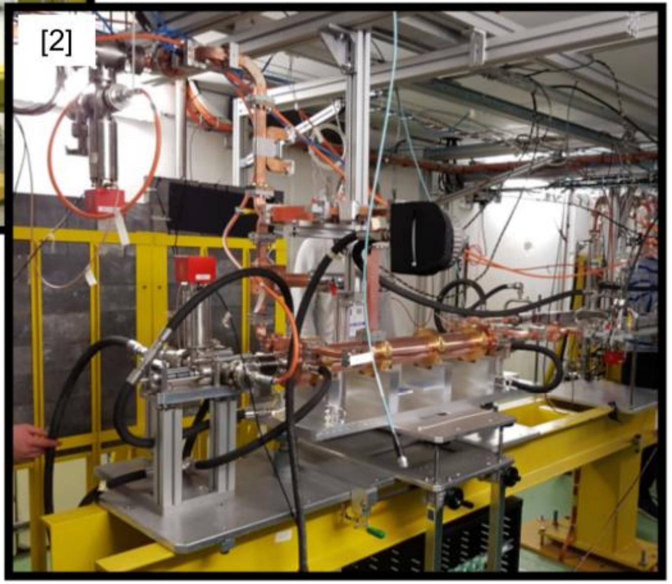


Bead-pull measurement at PSI

High power conditioning at CERN



[1] **V. Romano del Pozo, et al.**, in Proceedings of the 10th IPAC, 2019, pp. 2964–2967.

[2] **P. Craievich et al.**, in Proceedings of FEL'19, 2019, pp. 396–399.

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- Commissioning at FLASHForward finished
  + regular operation in PWFA experiments

FLASHForward

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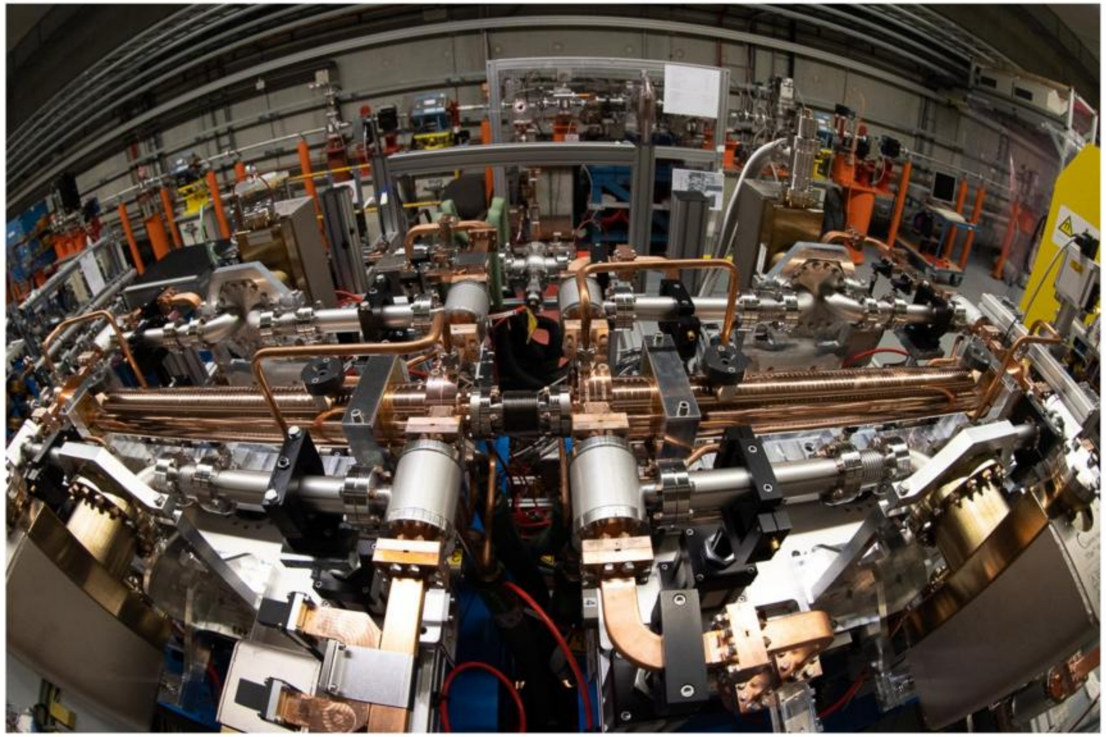
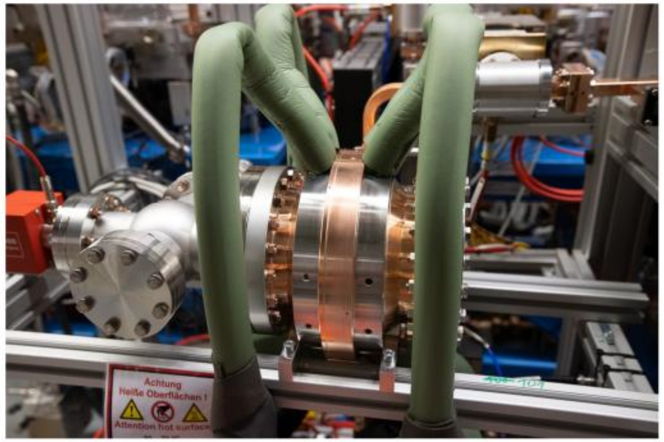
- Installation at **FLASH2** started

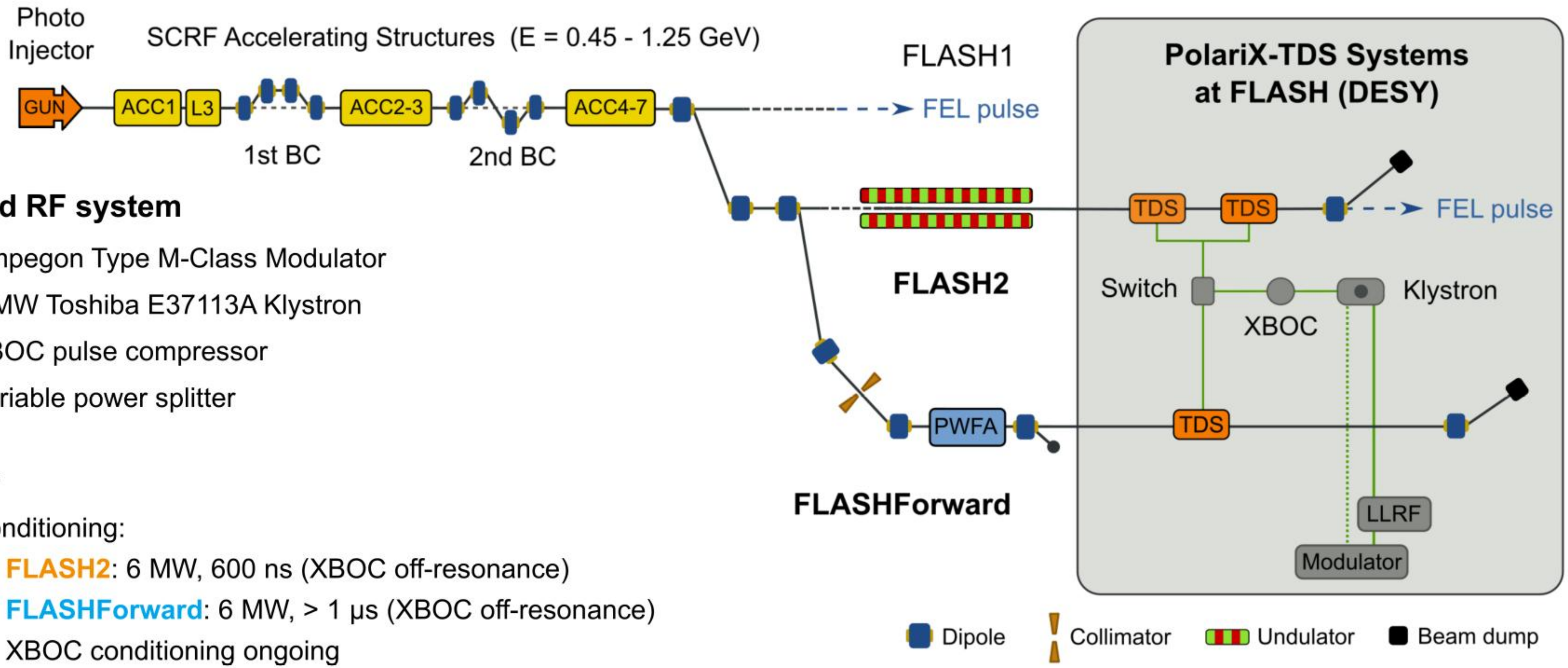
> 2021
- Installation and commissioning at FLASH2 finished
  + regular operation



FLASH2



FLASHForward [1] and FLASH2 [2] (DESY)



Shared RF system

- Ampegon Type M-Class Modulator
- 6 MW Toshiba E37113A Klystron
- XBOC pulse compressor
- Variable power splitter

Status

- Conditioning:
  - **FLASH2**: 6 MW, 600 ns (XBOC off-resonance)
  - **FLASHForward**: 6 MW, > 1 μs (XBOC off-resonance)
  - XBOC conditioning ongoing
- Regular operation at **FLASHForward** and **FLASH2**
- Expected resolution at **FLASHForward** / **FLASH2** ~ 1 fs (24 MW with XBOC)

[1] **R. D'Arcy et al.**, Phil. Trans. R. Soc. A 377, 20180392 (2019).
[2] **F. Christie et al.**, in Proc. FEL'19, 2019, pp. 328–331.

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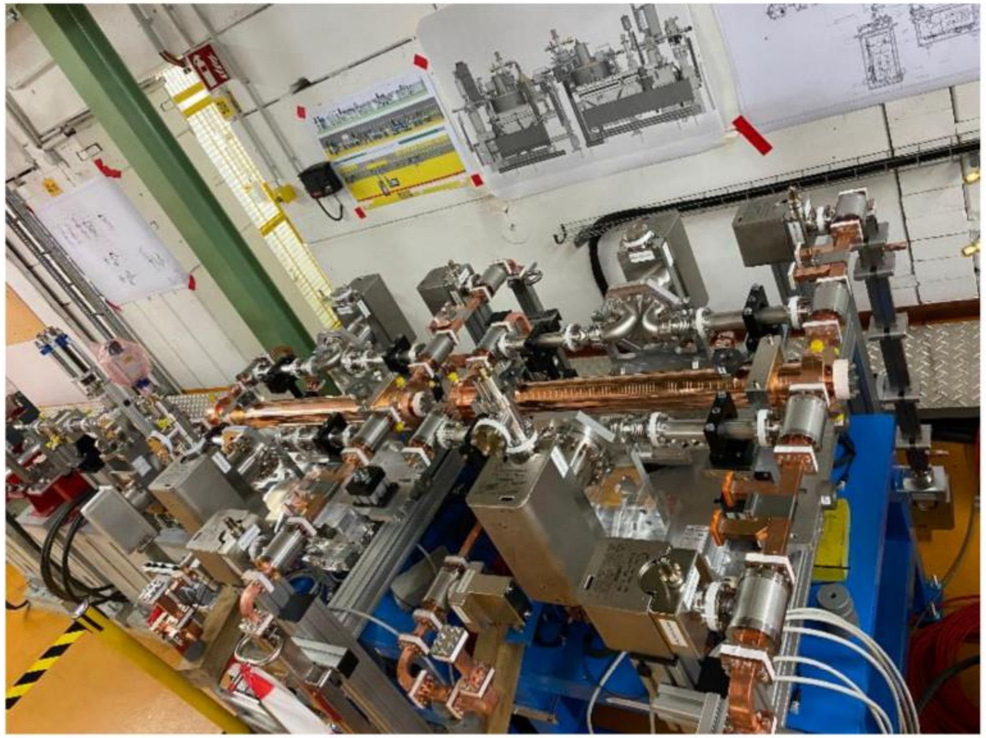
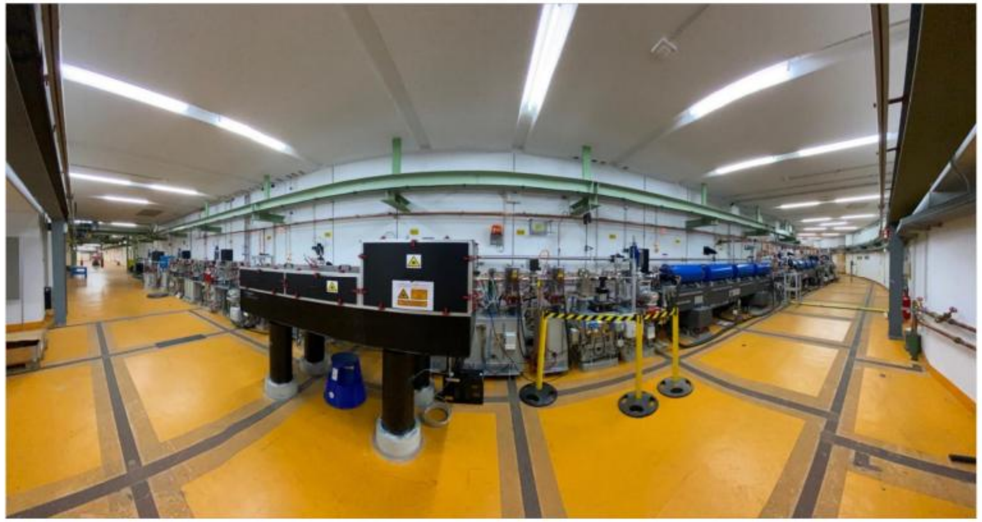
- Installation at **ARES** started



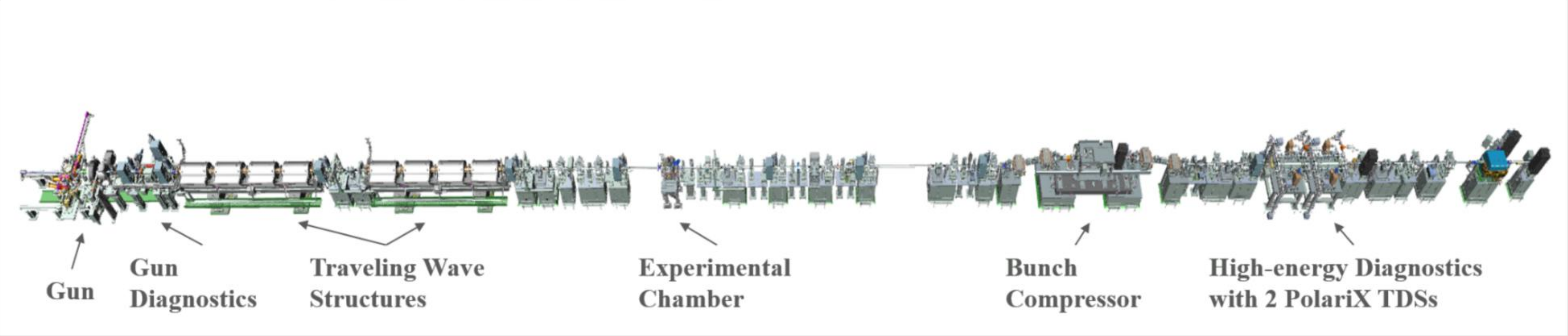
ARES



ARES-SINBAD [1] (DESY)

Status:

- 2 TDS, 1 XBOC and waveguides installed
- 2nd XBOC, Klystron and waveguides installation starting on Nov. 2021
- Facility commissioning started also in 2021
- Expected time resolution: sub-fs (24 MW with XBOC)



[1] **U. Dorda et al.**, Nucl. Instrum. Methods Phys. Res., Sect. A 29, 233 (2016).

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  - Installation at **FLASH2** started
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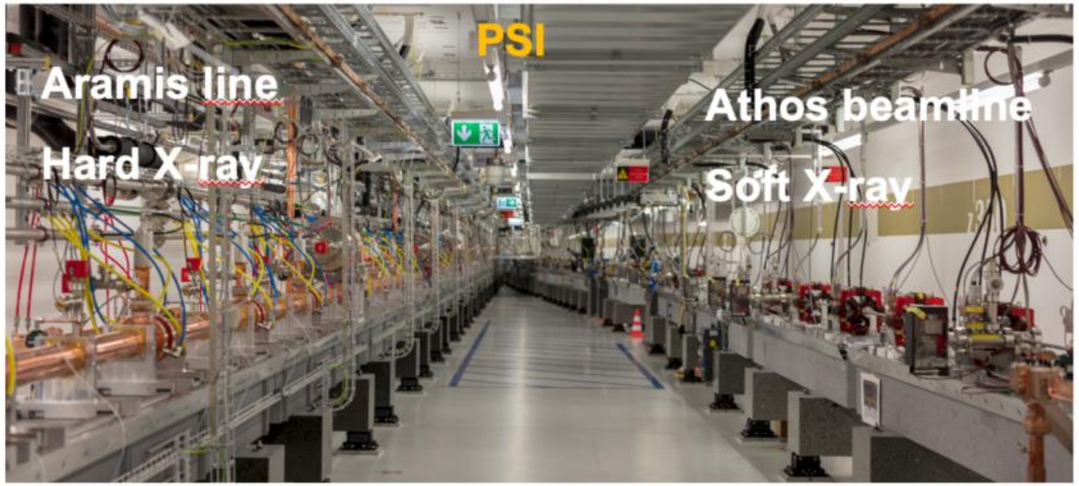
  - Installation at **ARES** started
  - Installation of RF structures and waveguide network at **ATHOS** finished



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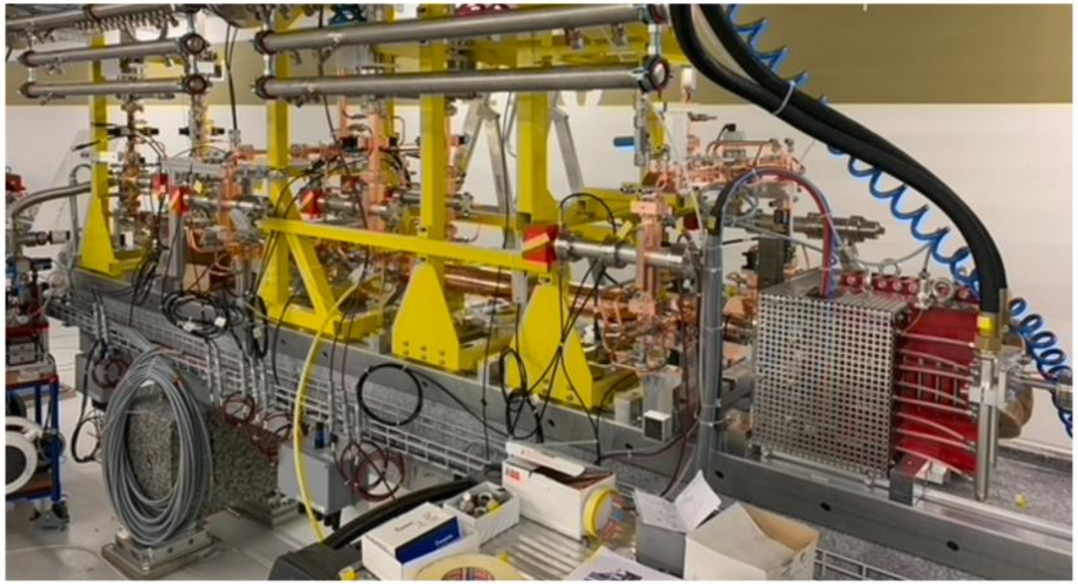
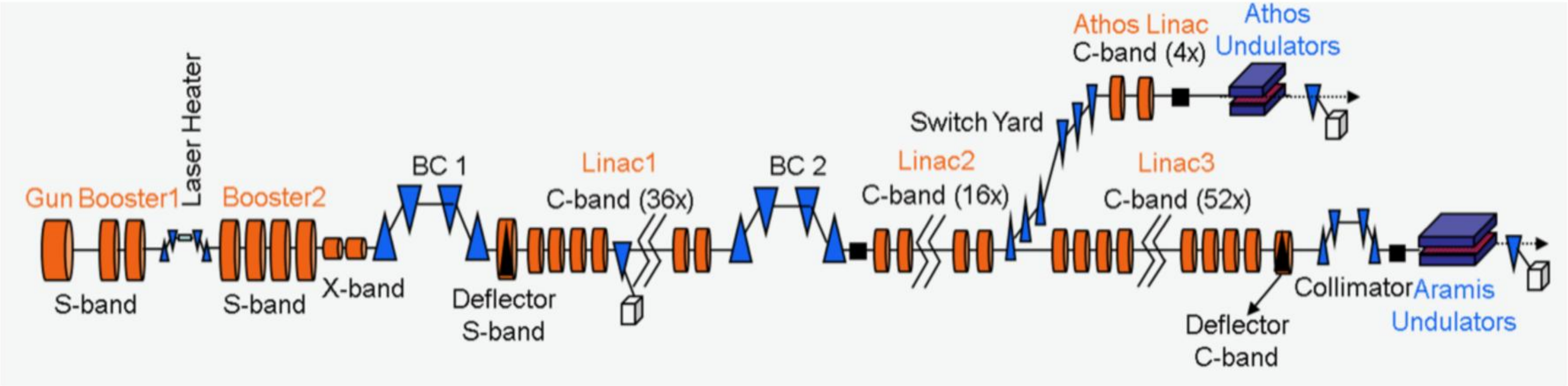


ATHOS [1] beamline at SwissFEL[2] (PSI)

Status:

- Beamline in operation
- Complete PolariX-TDS system installed (post-undulator), waiting for modulator
- Conditioning starts by end 2021 / beginning 2022
- Expected time resolution: sub-fs (20 MW with XBOC)

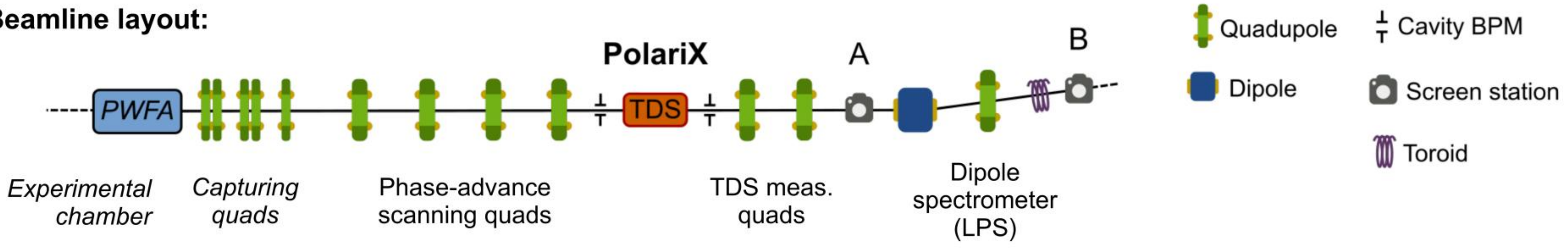


[1] **R. Ganter et al.**, J. Synchrotron Radiat. 26, 1073 (2019).

[2] **E. Prat et al.**, Nat. Photonics 14, 748–754 (2020)

FLASHForward X-TDS beamline

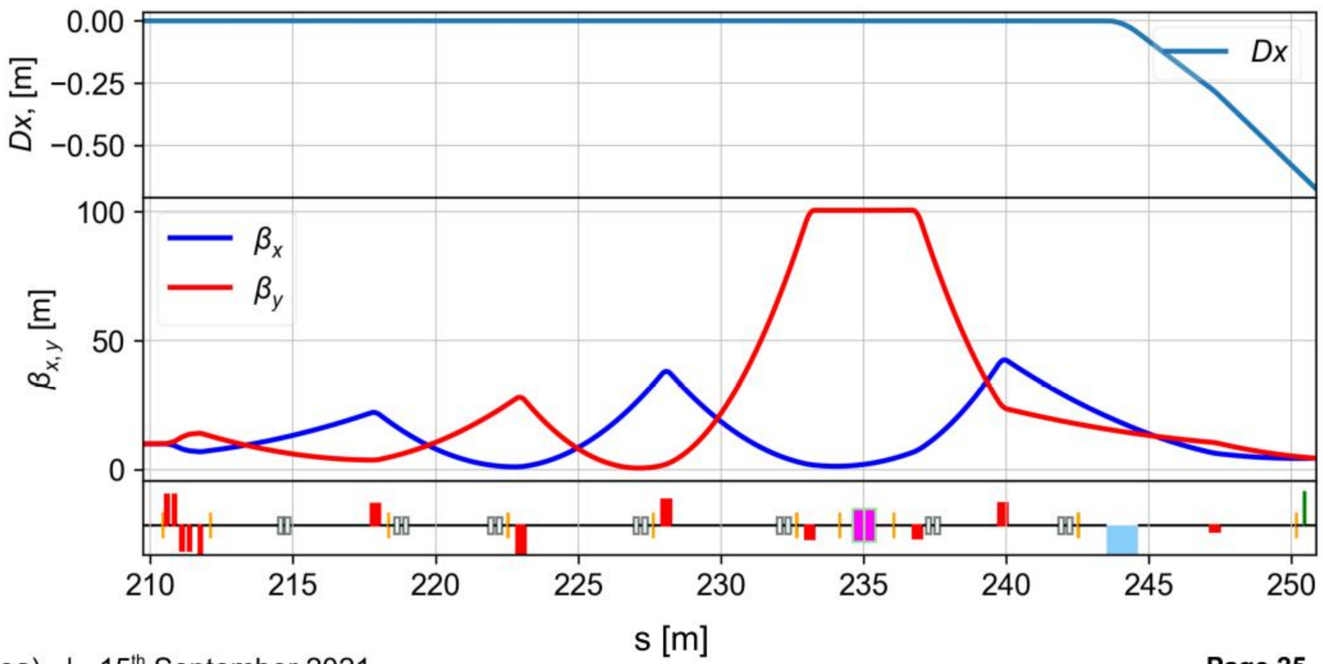
Beamline layout:



Diagnostics capabilities:

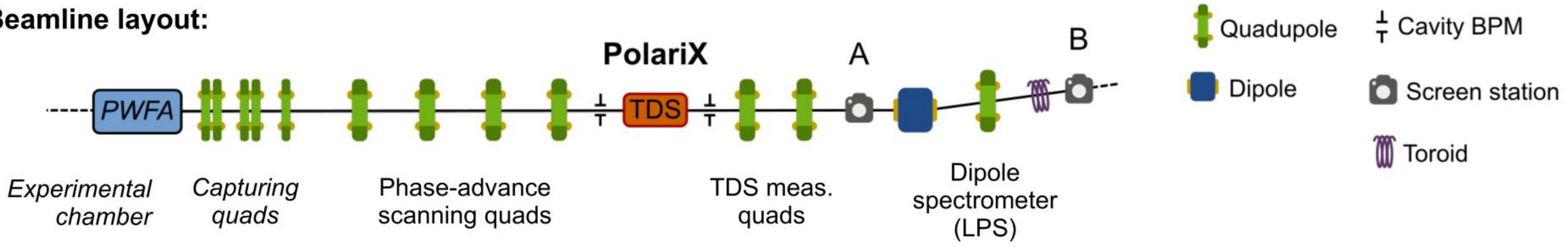
- Slice emittance measurements in *x* and *y* at screen A
- Longitudinal phase-space measurements at screen B
- Dipole spectrometer $|D_x| \leq 1$ m → energy resolutions $\leq 10^{-4}$

Lattice optic (B)



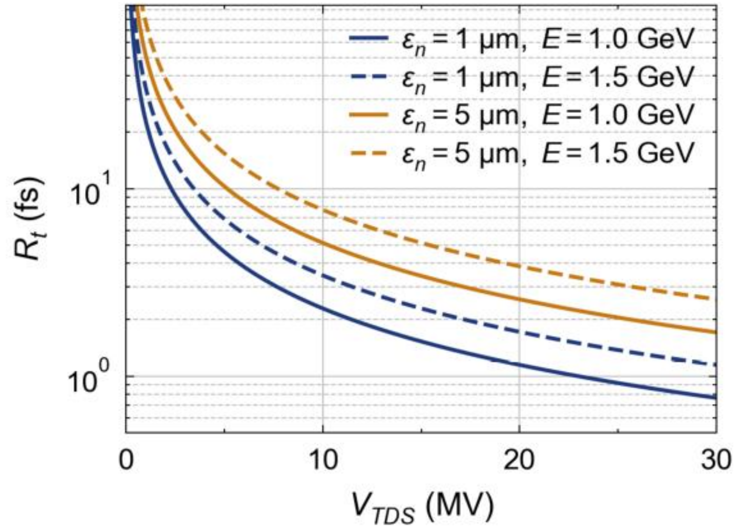
FLASHForward X-TDS beamline

Beamline layout:



Diagnostics capabilities:

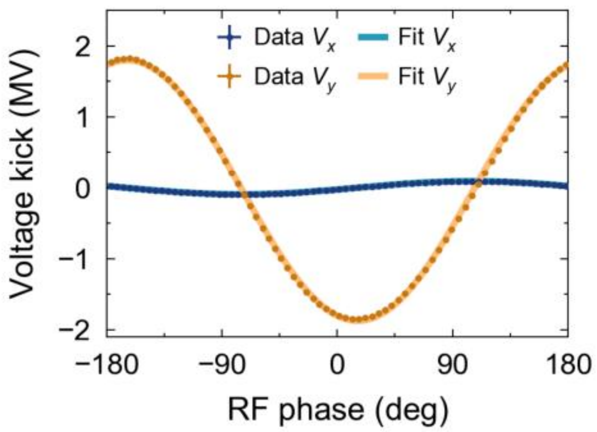
- Slice emittance measurements in x and y at screen A
- Longitudinal phase-space measurements at screen B
- Dipole spectrometer $|D_x| \leq 1$ m → energy resolutions ≤ 10^{-4}
- Time resolution with typical lattice-optic working point:
  - β_{TDS} ~ 100 m, $\psi_{TDS\text{-}SCR}$ ~ 90 deg
- Best time resolution achieved so far ~ 3 fs (V_{TDS} ~ 10 MV)



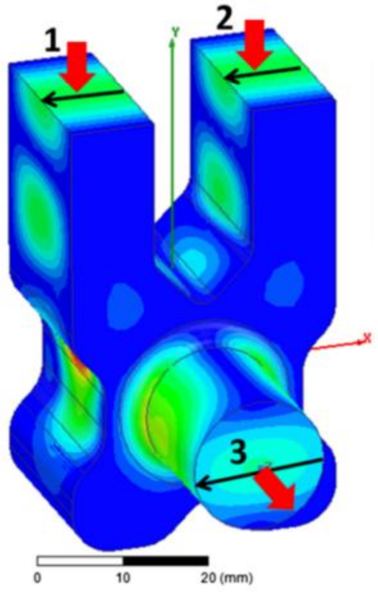
Beam-based commissioning at FLASHForward

RF parameters

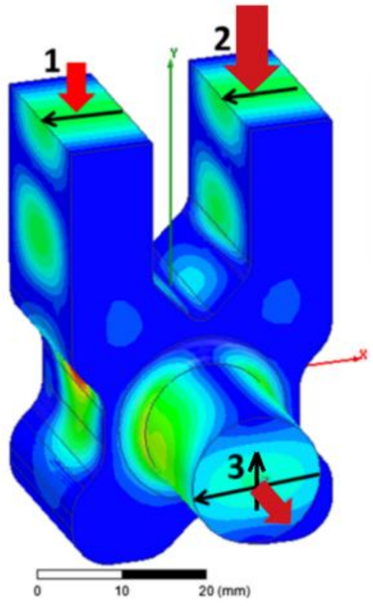
- Dipole field "purity" (360 deg RF phase scan):
  - slight kick due to power inbalance at inputs



Balanced inputs



Unbalanced inputs



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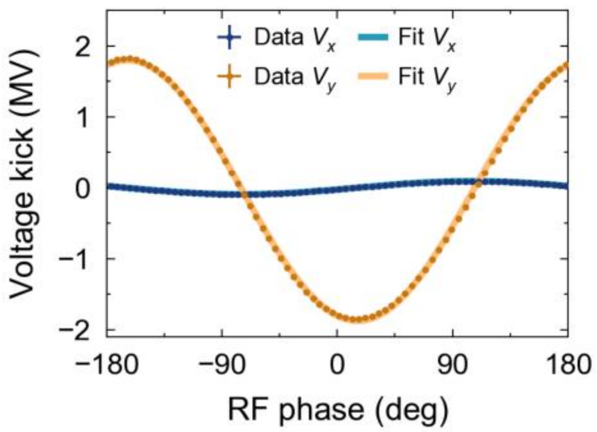
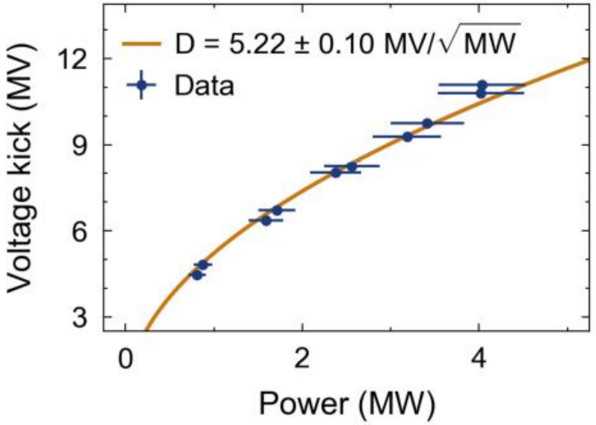


- Power-to-voltage (shunt impedance):
  - nominal values [1]:

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	$MV/MW^{0.5}$

  - excellent agreement with experiment



[1] **P. Craievich et al.**, in Proceedings of IPAC2018, 2018, pp. 3808–3811.

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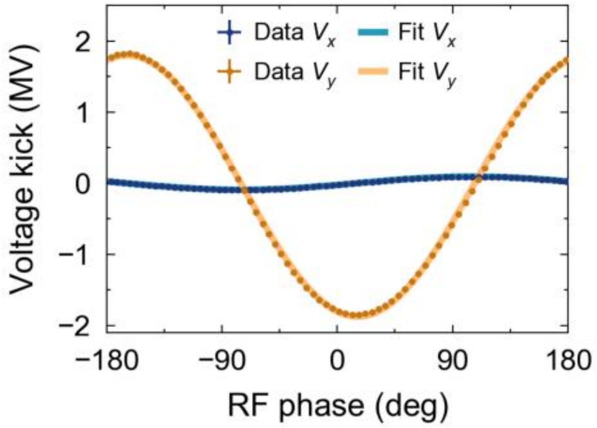

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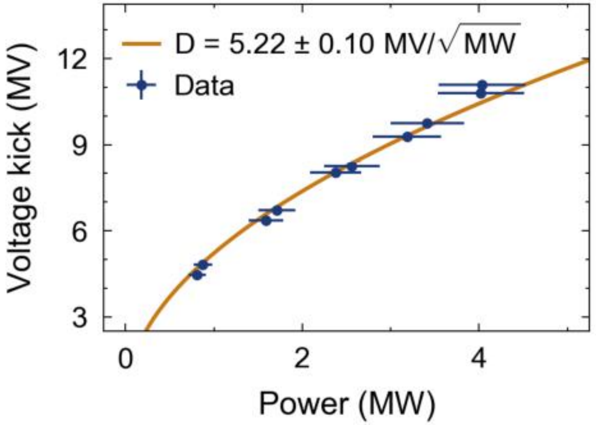
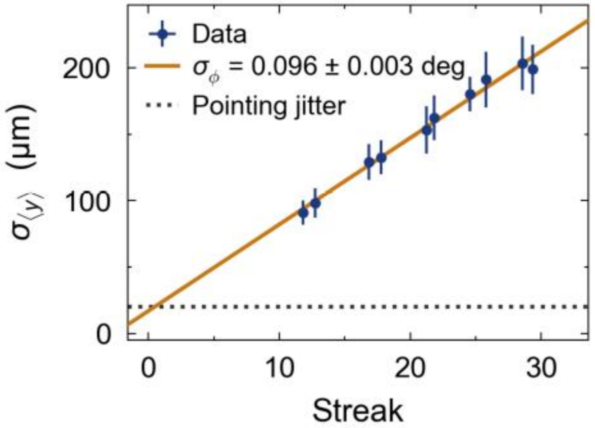


> Operation stability:
- phase jitter below requirements (σ_ϕ = 0.25 deg)
- amplitude jitter below linac compression jitter during shifts (σ_A < 3 %)



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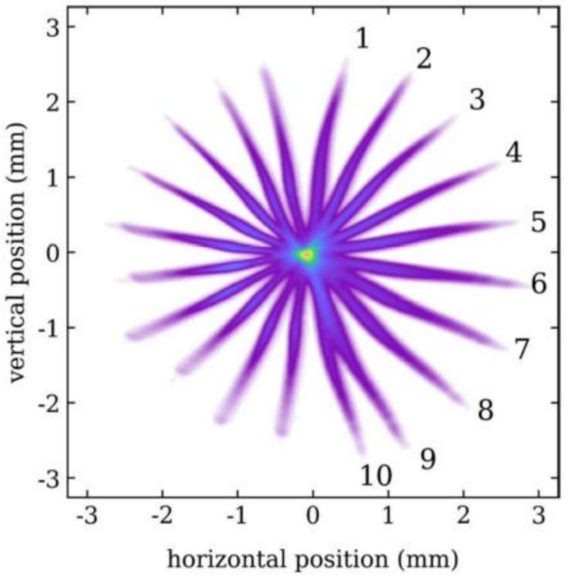
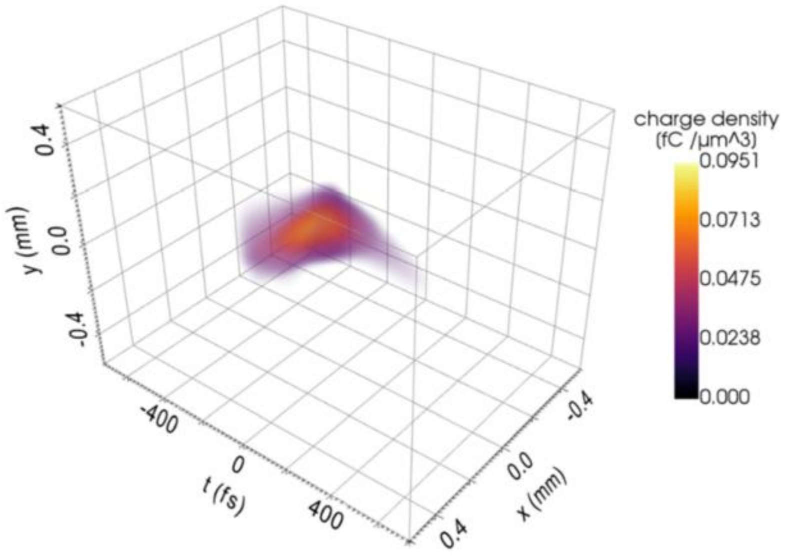
First Applications at FLASHForward

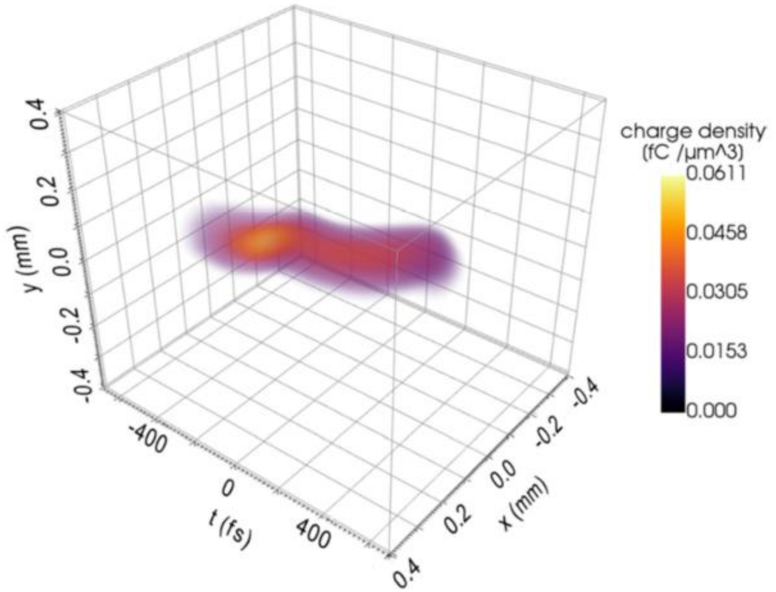
Beam characterisation I: 3D charge density reconstruction [1]

> Freely adjustable streak polarisation:
- fine control of phase-shifter



> 3D charge density reconstruction:
- symmetric lattice optics and drift between TDS and screen
- data sampled at 10 different angles (1st and 2nd zero crossing)
- novel tomographic reconstruction algorithm by D. Marx [2]





Visualisation by **S. Jaster-Merz**.

[1] **B. Marchetti et al.**, Sci Rep 11, 3560 (2021).

[2] **D. Marx et al.**,J. Phys.: Conf. Ser. 874 012077, 2017.

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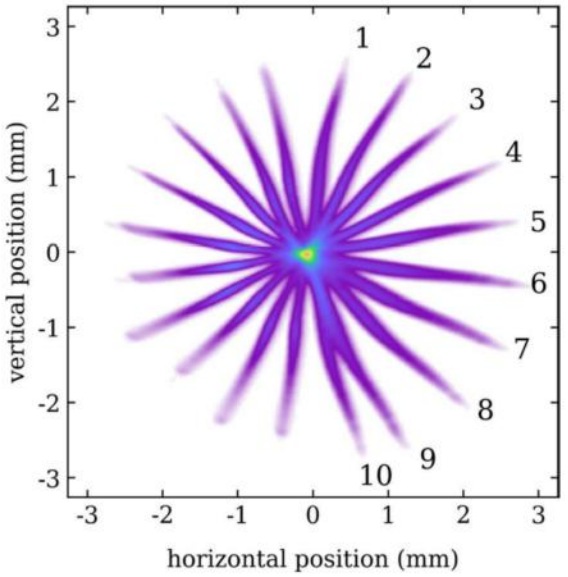

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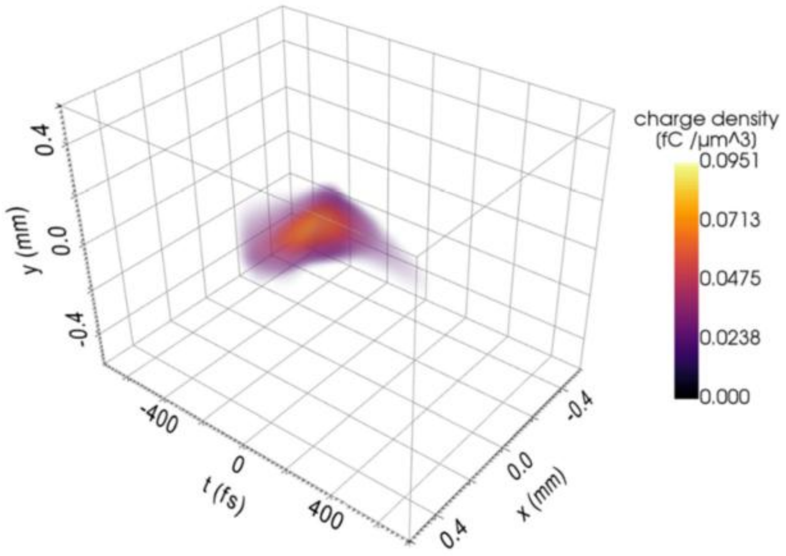

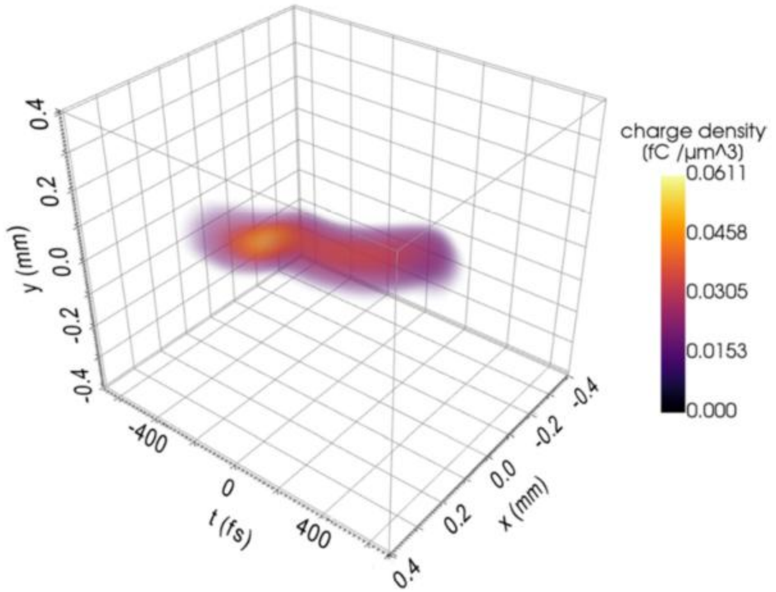

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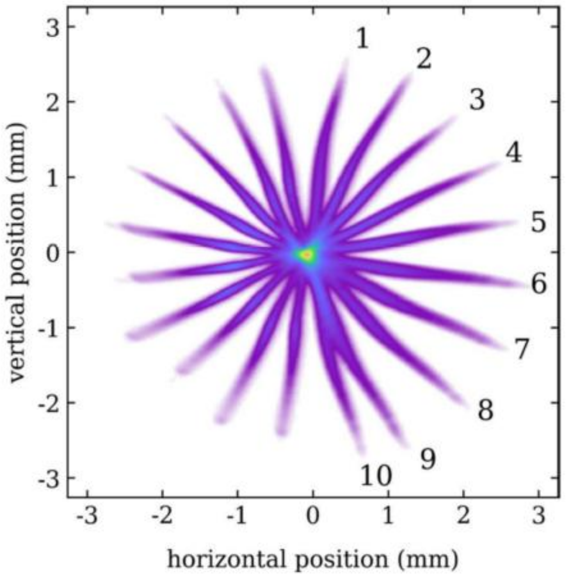

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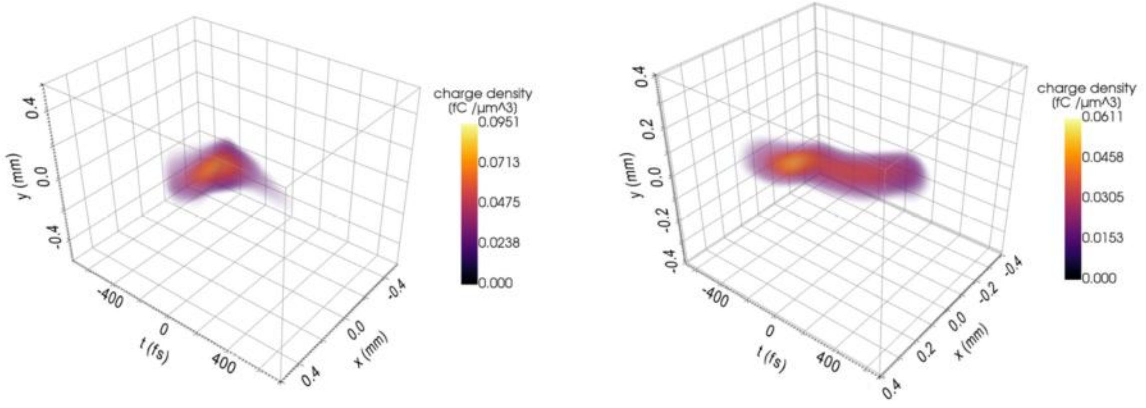


- Extension to **5D reconstruction** *(x, x', y, y', t)* being currently developed by S. Jaster-Merz [3]

[1] **B. Marchetti et al.**, Sci Rep 11, 3560 (2021).

[2] **D. Marx et al.**,J. Phys.: Conf. Ser. 874 012077, 2017.

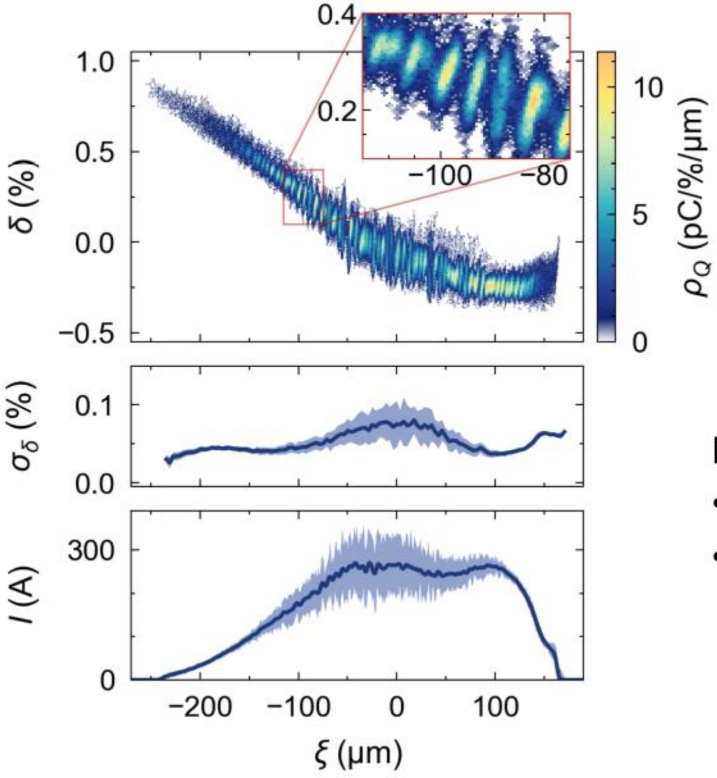
[3] **S. Jaster-Merz et al.**, IPAC'21, 2021, paper MOPAB302 (to be published)

First Applications at FLASHForward

Beam characterisation II: sliced bunch parameters (x, x', t) – (y, y', t) – (δ, t)

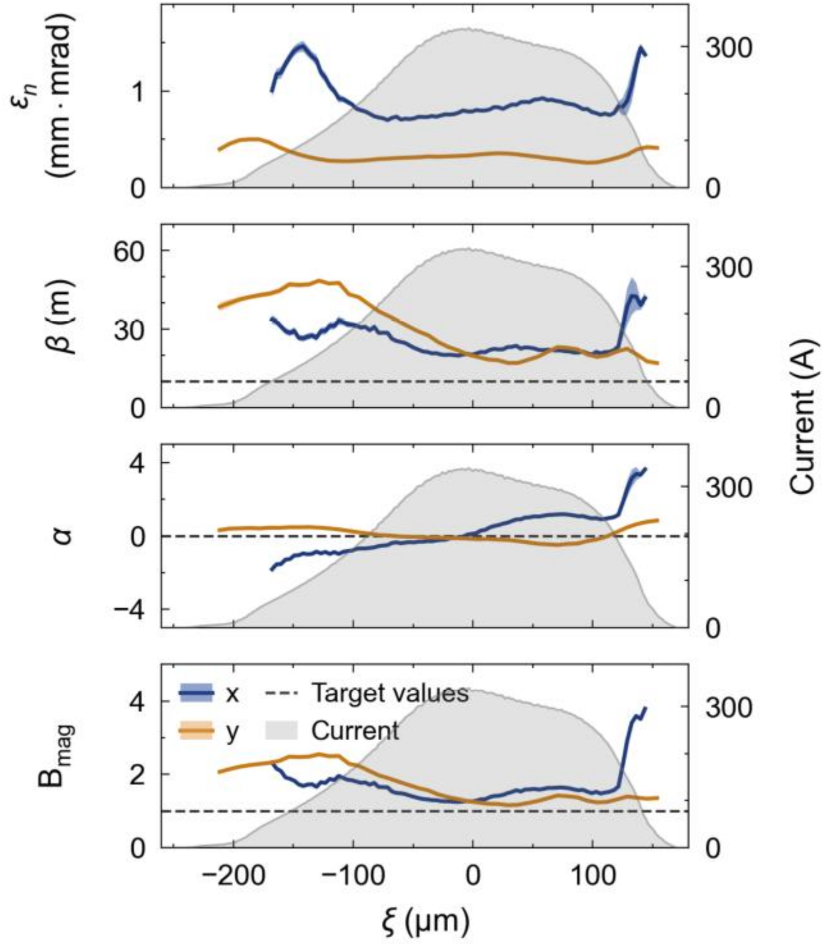
> Longitudinal phase space:
- time resolution R_t ~ 8 fs
- energy resolution R_δ ~ $6{\cdot}10^{-5}$
- estimated induced energy spread σ_{IES} ~ $6{\cdot}10^{-4}$

LPS (2nd zero crossing)



Bunch parameters:
- E = 750 MeV
- Q ~ 250 pC

> Slice emittance in *x* and *y*:
- time resolution in *y* / *x*: R_t ~ 9 fs / ~ 20 fs



First Applications at FLASHForward

Beam characterisation II: sliced bunch parameters (x, x', t) – (y, y', t) – (δ, t)

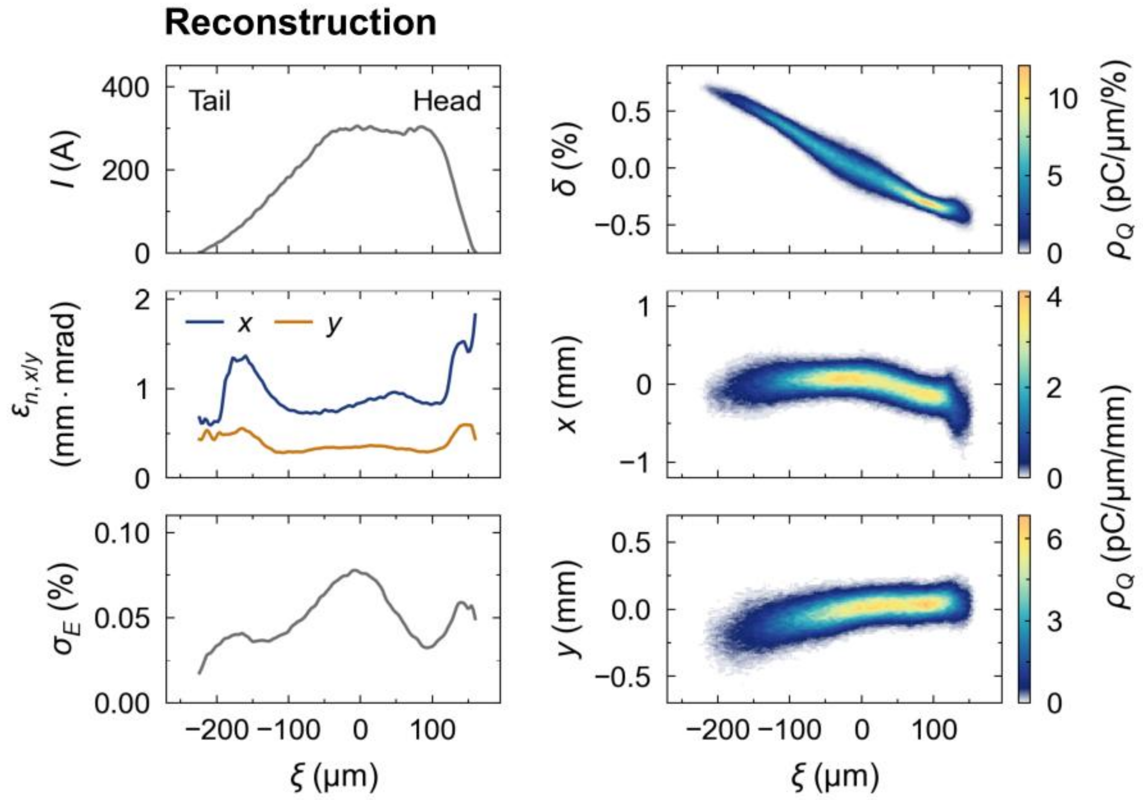
- For each slice t:
  - first moments:

$$\boldsymbol{X}_t = (\langle x \rangle, \langle x' \rangle, \langle y \rangle, \langle y' \rangle, \langle \xi \rangle, \langle \delta \rangle)$$

  - second moments:

$$\boldsymbol{\Sigma}_t = \begin{pmatrix} \begin{matrix} \langle x^2 \rangle & \langle xx' \rangle \\ \langle xx' \rangle & \langle x^2 \rangle \end{matrix} & 0 & 0 \\ 0 & \begin{matrix} \langle y^2 \rangle & \langle yy' \rangle \\ \langle yy' \rangle & \langle y^2 \rangle \end{matrix} & 0 \\ 0 & 0 & \begin{matrix} \langle \xi^2 \rangle & 0 \\ 0 & \langle \delta^2 \rangle \end{matrix} \end{pmatrix}$$

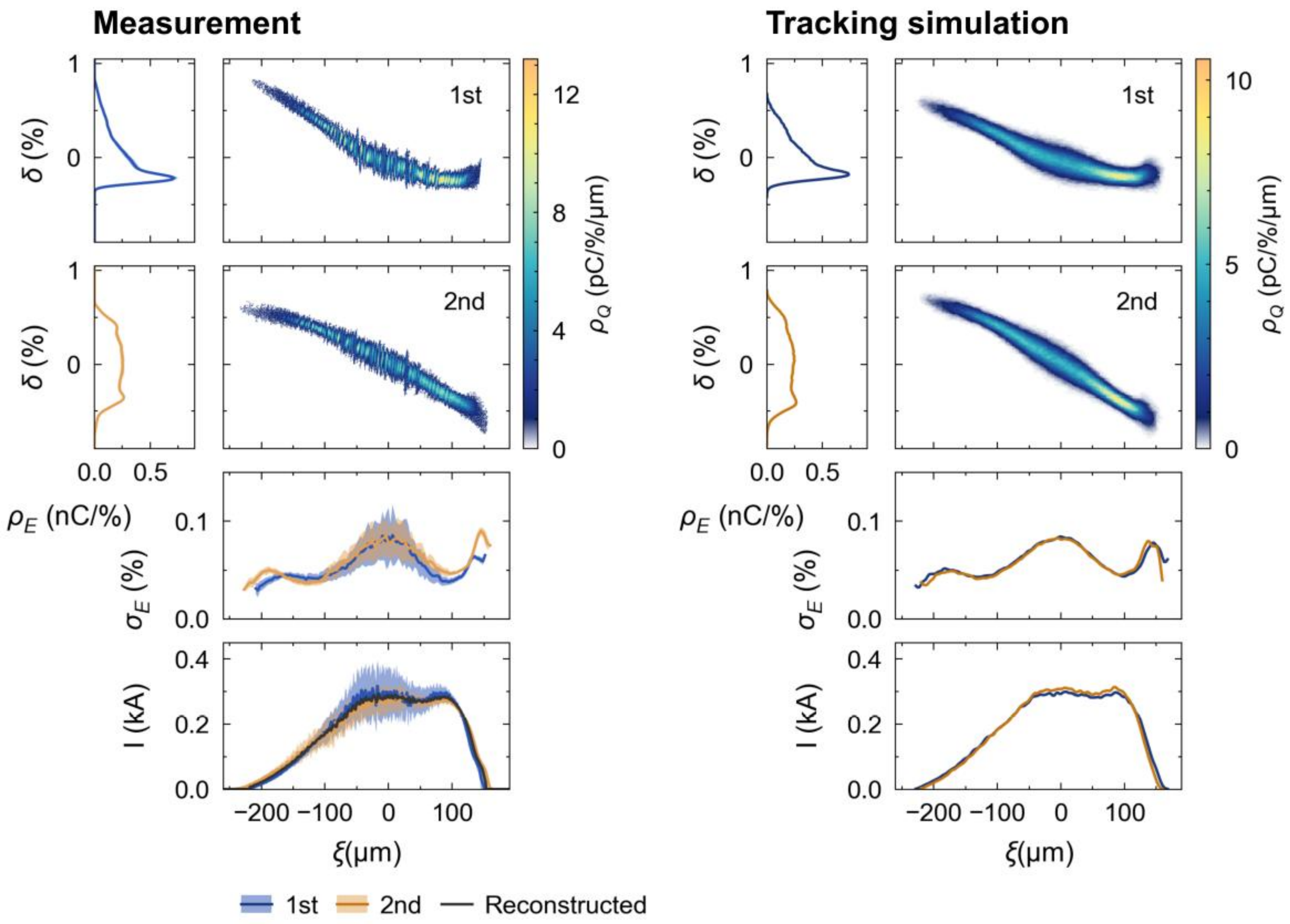
- Phase-space reconstruction:
  - combination of slice emittance and LPS



First Applications at FLASHForward

Beam characterisation II: sliced bunch parameters (x, x', t) – (y, y', t) – (δ, t)

> Phase-space reconstruction and particle tracking (OCELOT [1]):
  - very good agreement between experiment and simulation
  - bunch correlations (y, t) and (y', t) influence the LPS → difference between 1st and 2nd zero crossings

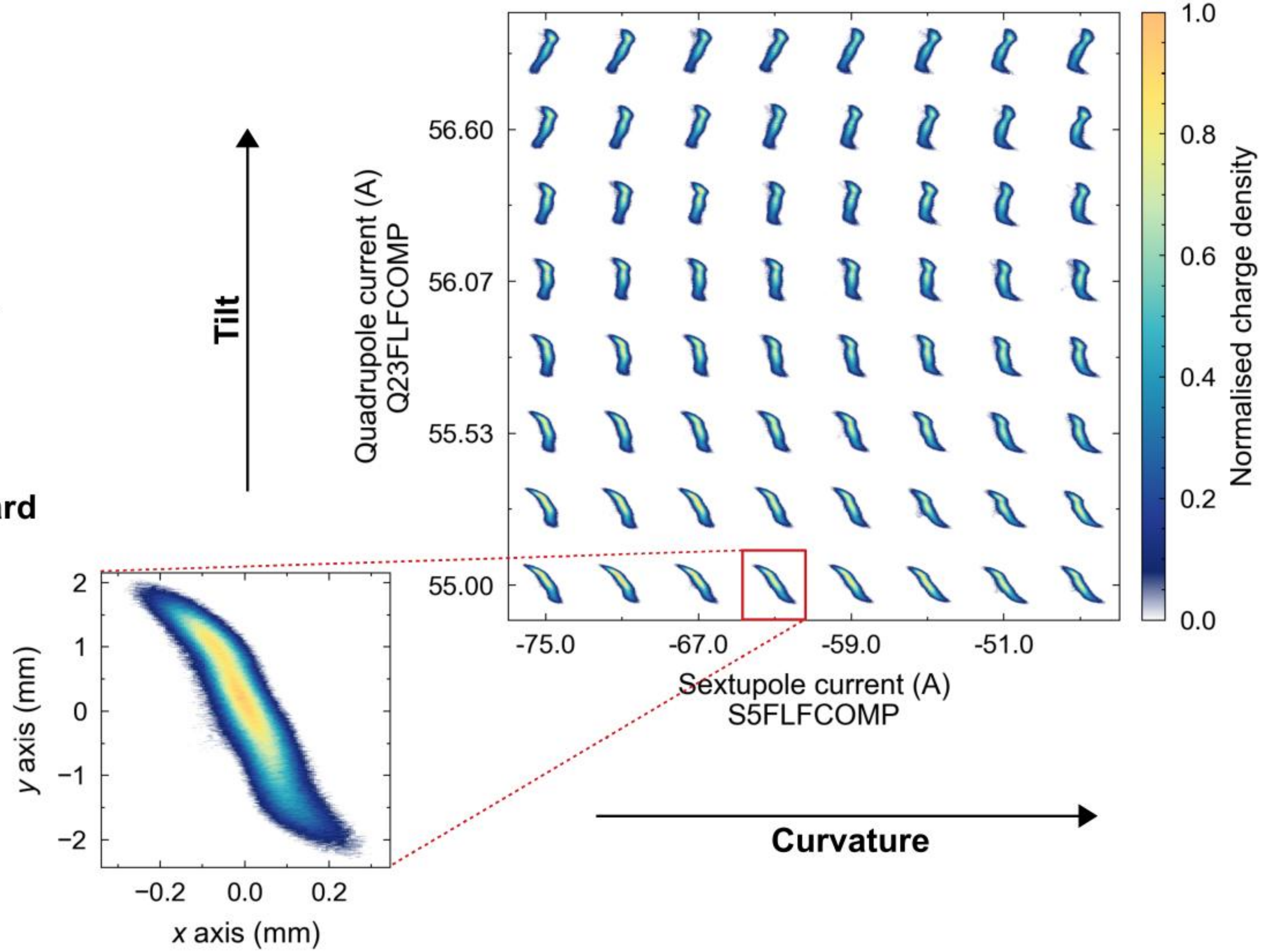


[1] **I. Agapov et al.**, Nucl. Instrum. Methods Phys. Res. A 768 (2014), pp. 151–156.

First Applications at FLASHForward

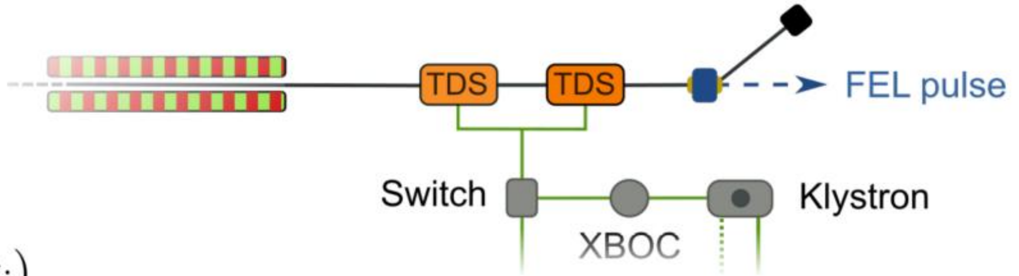
Dispersion-based beam-tilt correction for PWFA experiments

- Multiple sources of centroid offsets:
  - Coherent Synchrotron Radiation (CSR)
  - coupler kicks in linac modules
  - spurious dispersion
  - transverse wakefields
  - …
- Direct observation of beam tilts in *x* and *y* enabled by the **PolariX-TDS**
- Correction of tilt and curvature with magnets in a dispersive section
- Correction routines regularly applied at **FLASHForward**
- Critical for optimisation of PWFA experiments



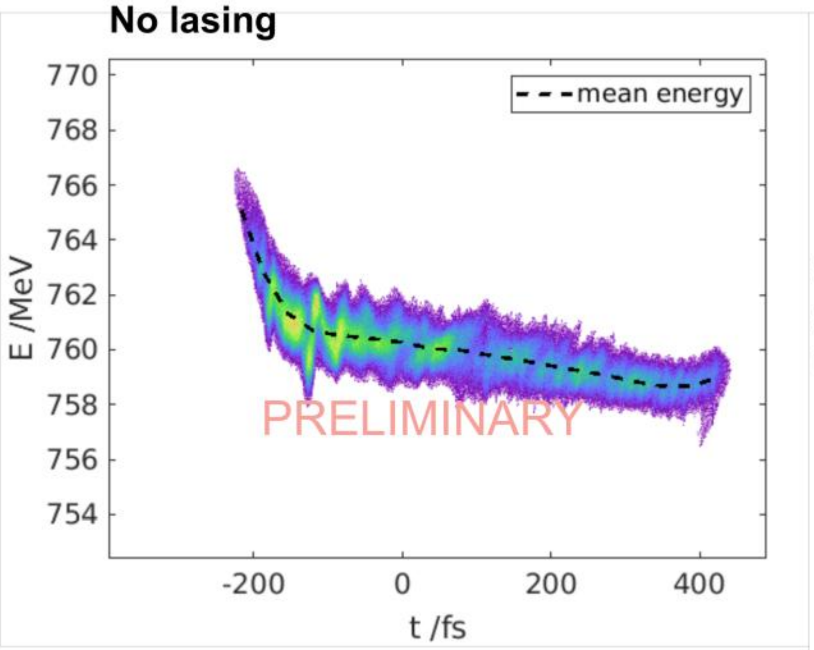
Preliminary results at FLASH2

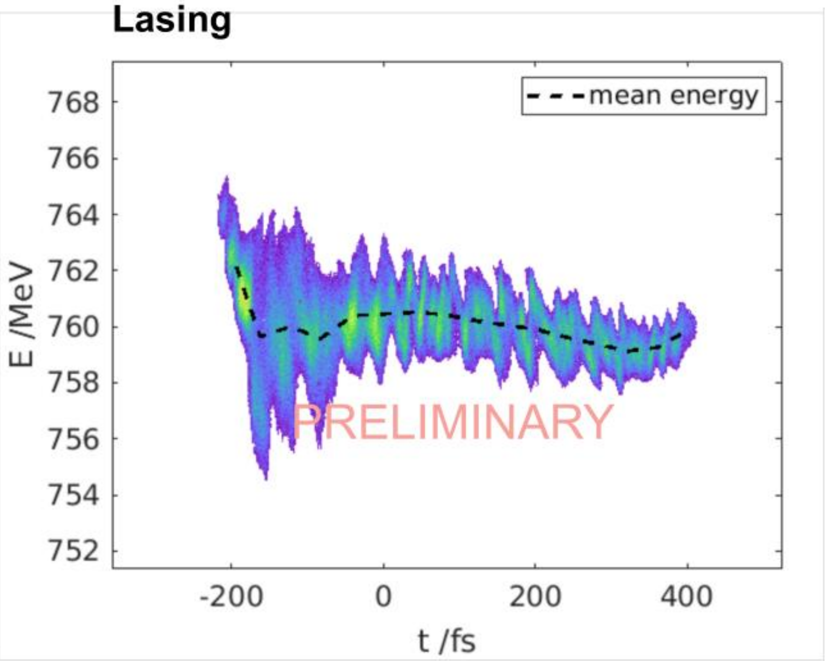
X-ray photon-pulse reconstruction*

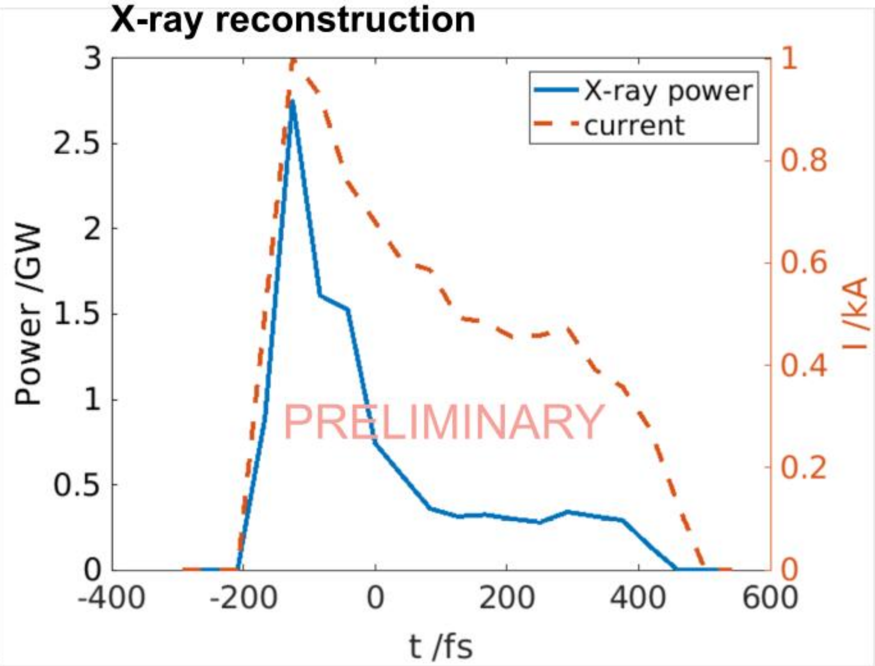


- Post-undulator diagnostic
- Time resolution: R_t ~ 12 fs
- Method employed: sliced mean energy loss [1]

$$P(t_i) = \Delta E(t_i) \cdot \frac{I(t_i)}{e}$$







[1] **F. Christie**, Ph.D. thesis, Universität Hamburg (2019), DESY-THESIS-2019-022.

Preliminary results at FLASHForward

Characterisation of PWFA-accelerated electron bunches

- Beam-driven plasma-wakefield produced in a pre-ionised plasma with density $n_0 \sim 10^{16}$ cm^{-3}
- External injection of 2nd (trailing) bunch in the wakefield
- Goal: quality preservation
  - demonstration of energy-spread preservation at **FLASHForward** in early 2021

PHYSICAL REVIEW LETTERS **126,** 014801 (2021)

Energy-Spread Preservation and High Efficiency in a Plasma-Wakefield Accelerator

C. A. Lindstrøm,[1,*] J. M. Garland,[1] S. Schröder,[1,2] L. Boulton,[1,3,4] G. Boyle,[1] J. Chappell,[5] R. D'Arcy,[1] P. Gonzalez,[1,2] A. Knetsch,[1,†] V. Libov,[1] G. Loisch,[1] A. Martinez de la Ossa,[1] P. Niknejadi,[1] K. Põder,[1] L. Schaper,[1] B. Schmidt,[1] B. Sheeran,[1,2] S. Wesch,[1] J. Wood,[1] and J. Osterhoff[1]

[1]*Deutsches Elektronen-Synchrotron DESY, Notkestraße 85, 22607 Hamburg, Germany*
[2]*Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany*
[3]*SUPA, Department of Physics, University of Strathclyde, Glasgow, United Kingdom*
[4]*The Cockcroft Institute, Daresbury, United Kingdom*
[5]*University College London, London, United Kingdom*

(Received 21 July 2020; revised 5 November 2020; accepted 8 December 2020; published 6 January 2021)

Energy-efficient plasma-wakefield acceleration of particle bunches with low energy spread is a promising path to realizing compact free-electron lasers and particle colliders. High efficiency and low energy spread can be achieved simultaneously by strong beam loading of plasma wakefields when

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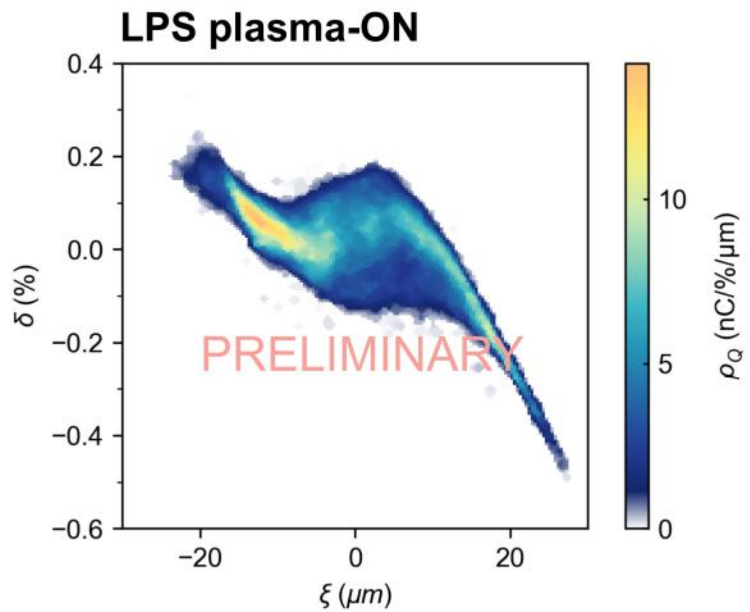
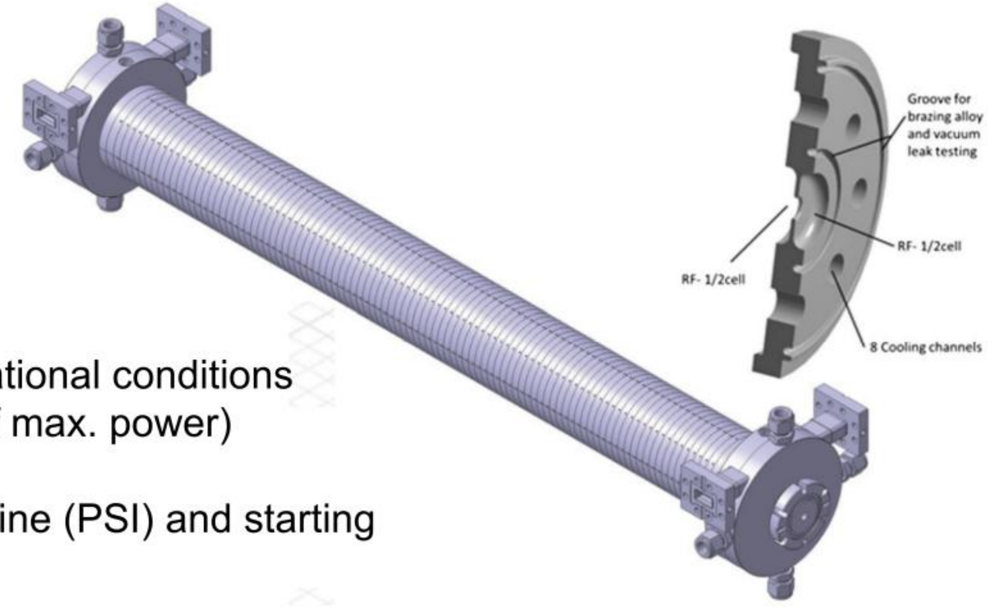
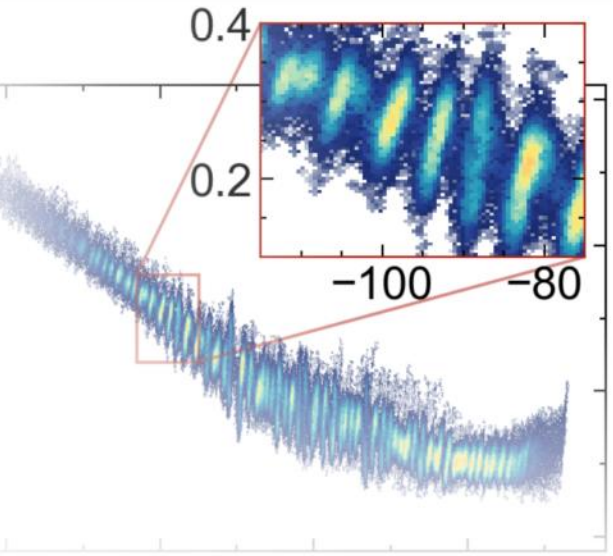
- Beam-driven plasma-wakefield produced in a pre-ionised plasma with density $n_0 \sim 10^{16}$ cm^{-3}
- External injection of 2nd (trailing) bunch in the wakefield
- Goal: quality preservation
  - demonstration of energy-spread preservation at **FLASHForward** in 2021 [1]
- Further study of acceleration process with **PolariX-TDS** system
  - longitudinal phase space of electron bunches accelerated in a ~ 1 GV/m E_z field
  - comparison with plasma-off LPS can give key insights into the plasma-acceleration process



Summary and outlook



- **PolariX-TDS** prototype has been developed, implemented, and successfully commissioned by an international collaboration.
- System installed at **FLASHForward** and **FLASH2** (DESY) in advanced operational conditions and validating femtosecond-scale longitudinal resolutions of R_t ~ 3 fs (at ¼ of max. power)
- System installed at **ARES-SINBAD** (DESY) and at **ATHOS-SwissFEL** beamline (PSI) and starting RF conditioning very soon.
- Prototype commissioning at **FLASHForward** shows excellent agreement with nominal design parameters and RF phase stability σ_ϕ < 0.1 deg.
- 3D tomographic reconstruction enabled by the **PolariX-TDS** has been demonstrated.
- Advanced diagnostics applications for novel accelerator concepts and FELs have been shown.
- Promising preliminary results in PWFA and FEL diagnostics have been obtained with further analysis ongoing.



Thanks for your attention!

Live talk and discussion:

Wednesday 15th of September at 22:10 (Seoul) / 15:10 (Berlin)

Pau González Caminal
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E-Mail: pau.gonzalez@desy.de