X-Band TDS simulations and commissioning

EAAC 2019, Isola d'Elba, Italy – 19th September 2019

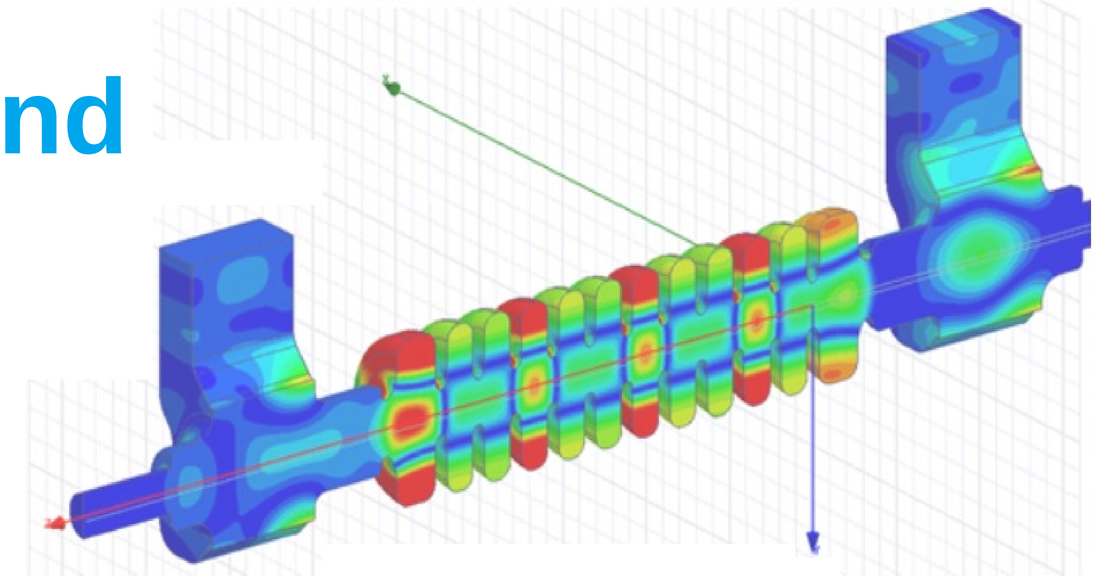


Figure courtesy of **A. Grudiev** (CERN).

P. Gonzalez, R. D'Arcy, J. Garland, C. A. Lindstrøm, K. Ludwig, F. Marutzky, S. Wesch, J. Osterhoff

FLASHForward ▸▸ | Research Group for Plasma Wakefield Accelerators FLA-PWA (DESY)

B. Marchetti, R. Assmann, B. Beutner, J. Brandlard, F. Christie, W. Decking, U. Dorda, J. Herrmann, M. Hoffmann, M. Huening, O. Krebs, G. Kube, S. Lederer, D. Marx, I. Peperkorn, S. Pfeiffer, F. Pototzki, J. Roensch-Schulenburg, J. Rothenburg, H. Schlarb, M. Scholz, S. Schreiber, M. Vogt, A. de Z. Wagner, T. Wilksen, K. Wittenburg – Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

A. Grudiev, N. Catalan Lasheras, G. Mcmonagle, W. Wuensch – CERN, Geneva, Switzerland

P. Craievich, M. Bopp, H.-H. Braun, M. Pedrozzi, E. Prat, S. Reiche, K. Rolli, R. Zenaro – PSI, Villigen, Switzerland

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES | MT ARD | Universität Hamburg DER FORSCHUNG | DER LEHRE | DER BILDUNG | PIER Eine Partnerschaft der Universität Hamburg und DESY | PAUL SCHERRER INSTITUT PSI | CERN | DESY.

PolariX TDS Project – Advanced Diagnostics for fs Bunches

- Novel design of TDS with **tunable direction of streaking field invented at CERN (Alexej Grudiev)**
- Cavity design matches specifications of 4 experiments: **FLASHForward, FLASH2, SINBAD/ARES at DESY and ATHOS beamline at PSI.**
- The cavity has been manufactured at PSI using the **tunning free assembly procedure**
- Device prototyped at **FLASHForward**
- Achievable **time resolutions at FFWD on > 1 fs**

Collaboration between:

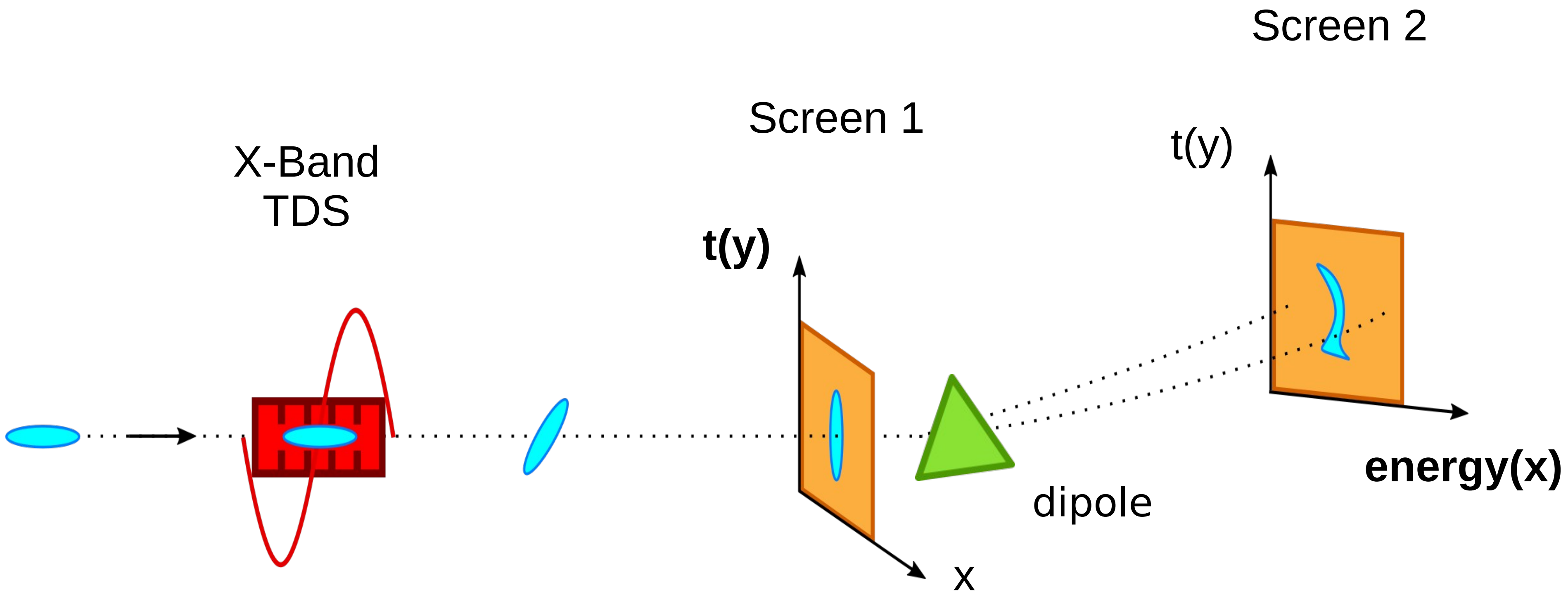
PAUL SCHERRER INSTITUT

Coordinated by:
A. Grudiev (CERN), P. Craievich (PSI),
B. Marchetti (DESY)

Gerardo D'Auria – Plenary talk 17.09.2019, 11:00

Barbara Marchetti – WG4 17.09.2019, 18:00

X-Band TDS Principles Of Operation



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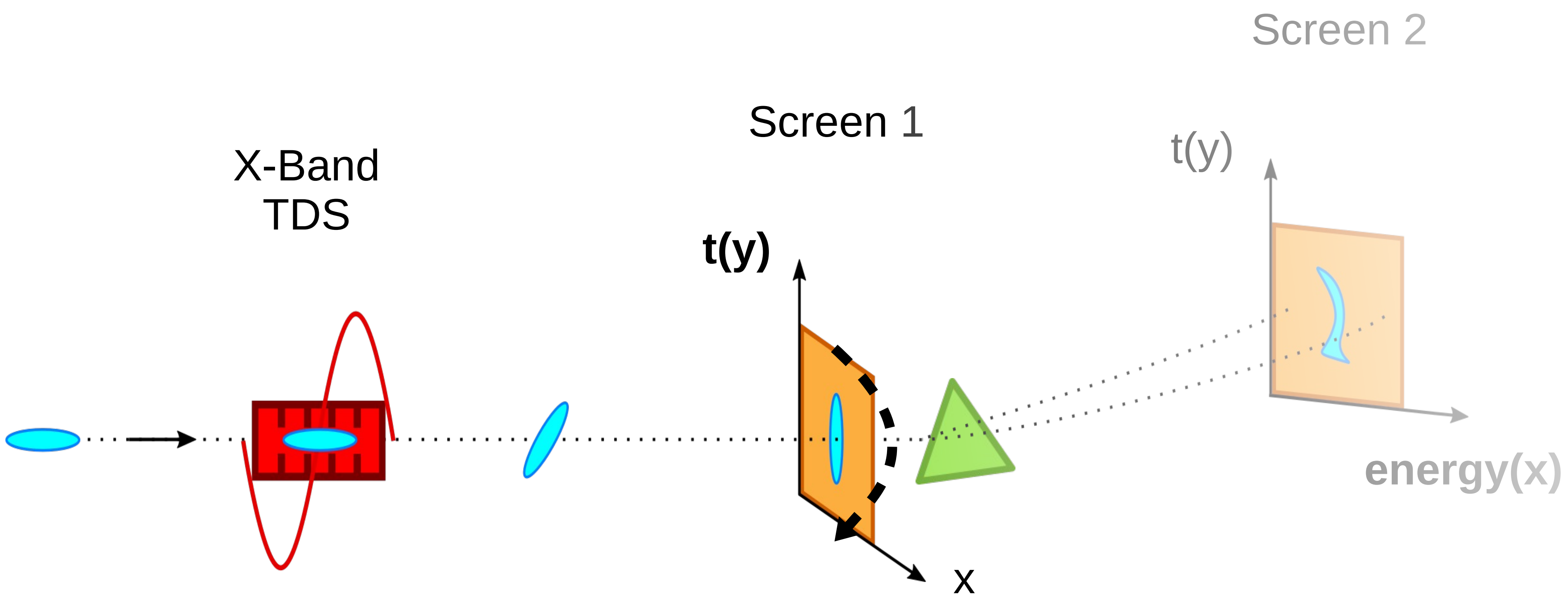
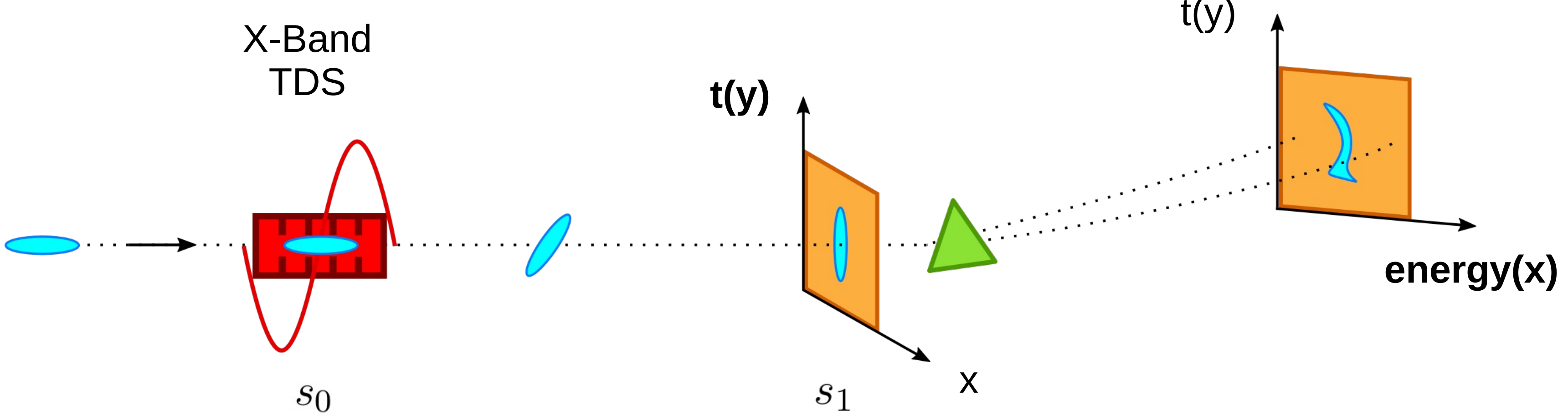


+ variable polarization of streaking field

X-Band TDS Resolution

- Time resolution



$$y(s) = y_\beta(s) + S_y(s) \cdot \zeta \longrightarrow \sigma_y = \sqrt{\sigma_{y\beta}^2 + S_y^2 \cdot \sigma_\zeta^2} \longrightarrow \sigma_\zeta > \frac{\sigma_{y\beta}(s_1)}{S_y(s_1)} = R_\zeta$$

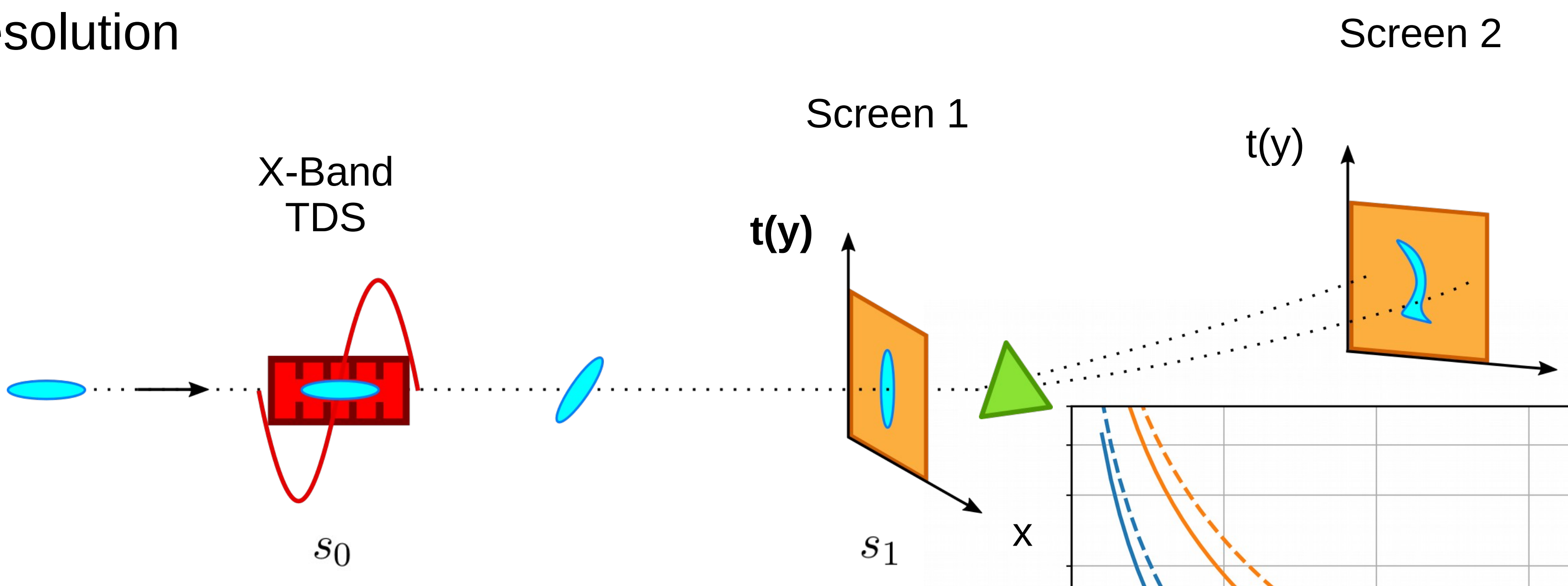
with: $\sigma_{y\beta} = \sqrt{\epsilon_y \cdot \beta_y(s_1)}$

$$S_y(s_0, s_1) = \sqrt{\beta_y(s_0)\beta_y(s_1)} \cdot \sin \Delta\Psi_y \cdot \frac{eV_0 k}{pc}$$

$$R_\zeta = \frac{\sigma_{y\beta}}{S_y} = \sqrt{\frac{\epsilon_y}{\beta(s_0)}} \cdot \frac{1}{\sin \Delta\Psi_y} \cdot \frac{pc}{eV_0 k}$$

X-Band TDS Resolution

- Time resolution



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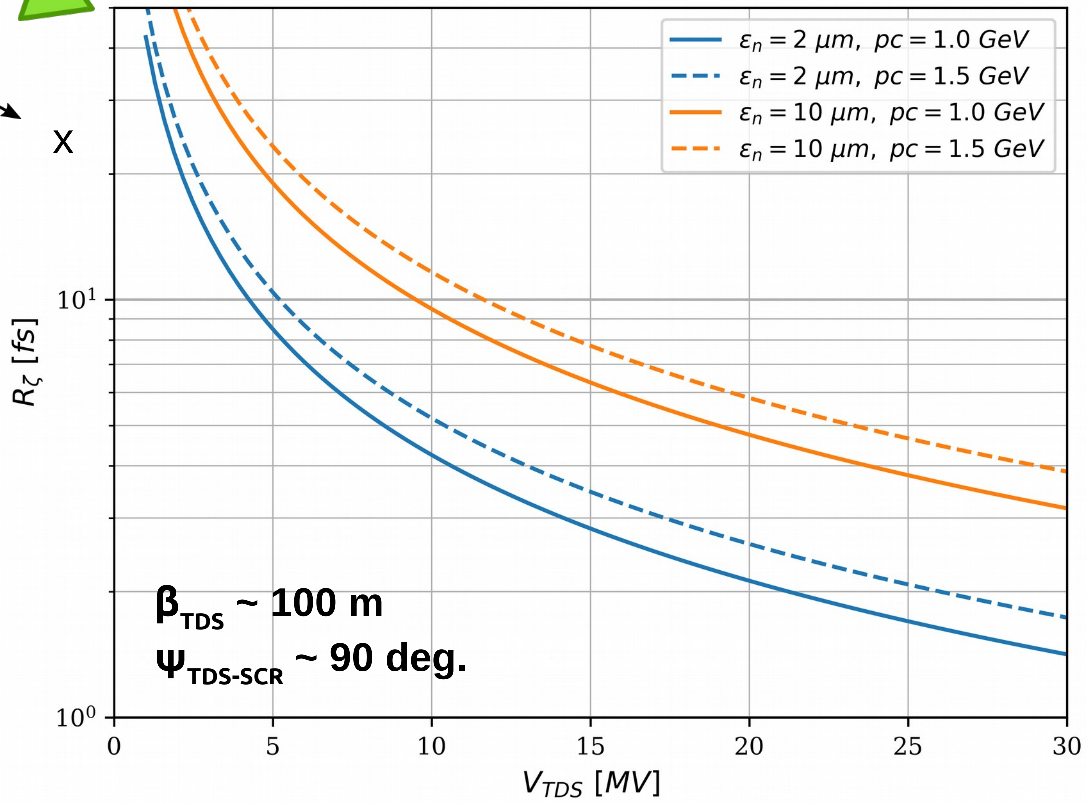
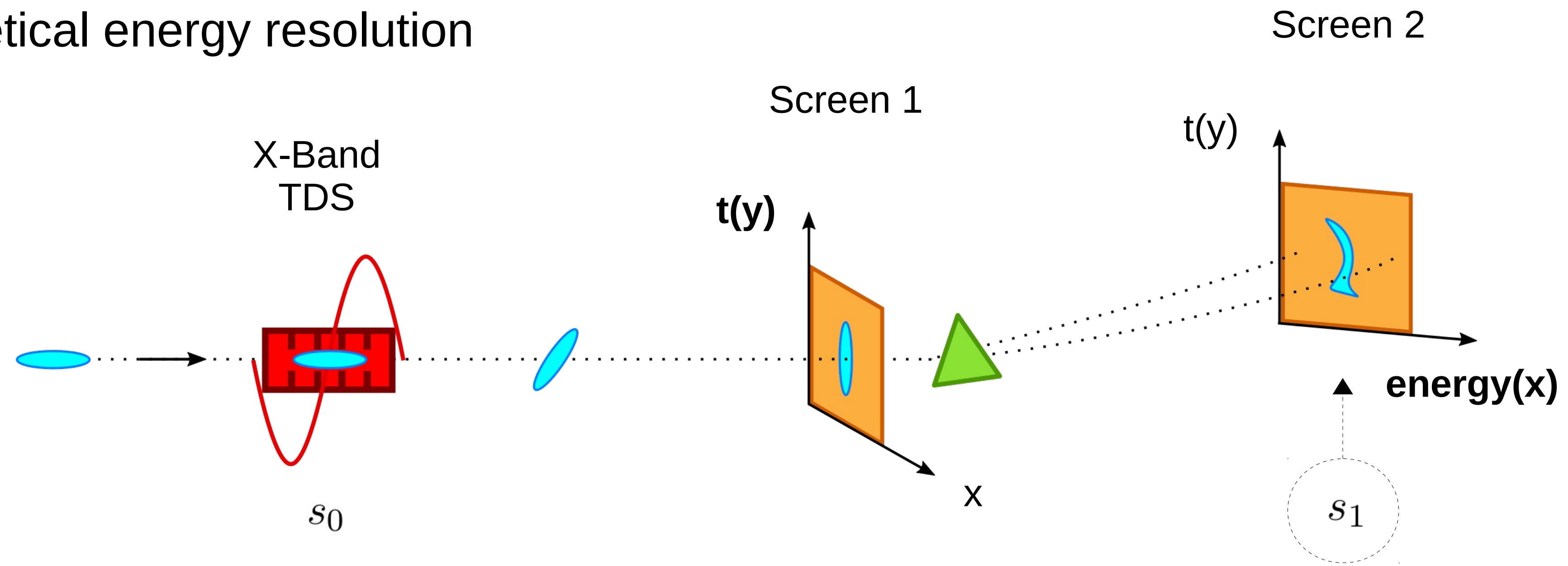


X-Band TDS Resolution

> Theoretical energy resolution



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X-Band TDS Resolution

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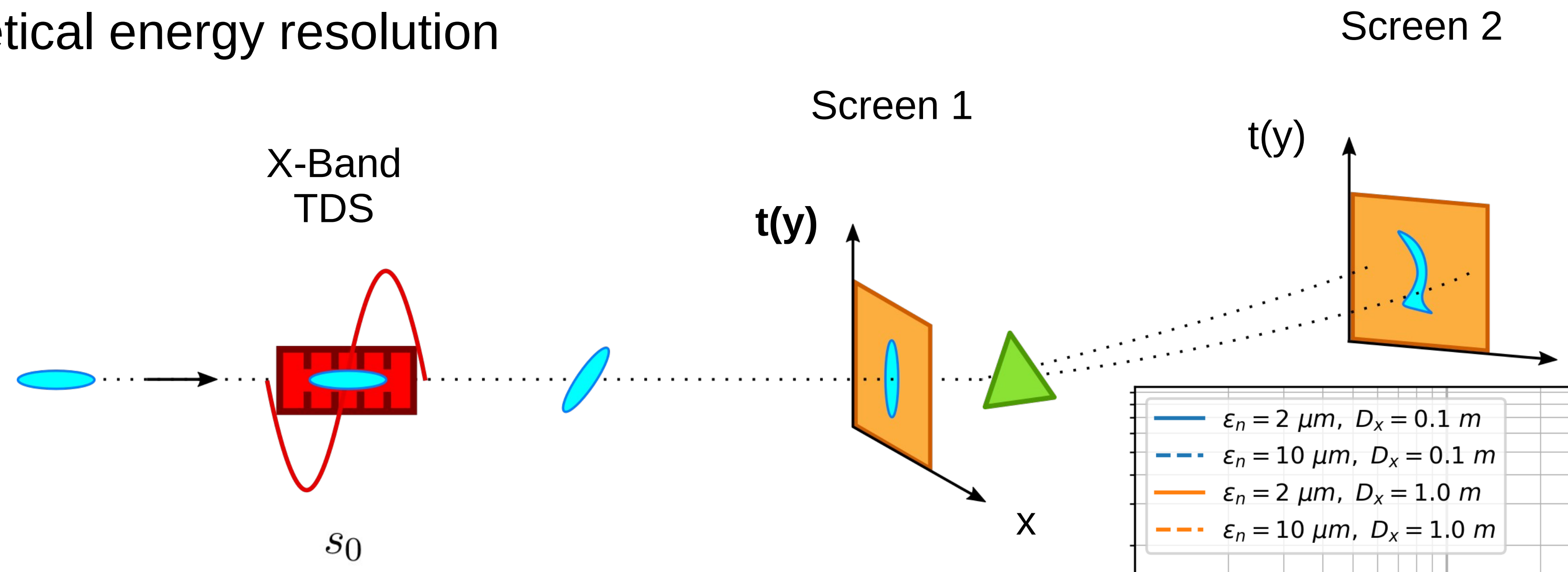

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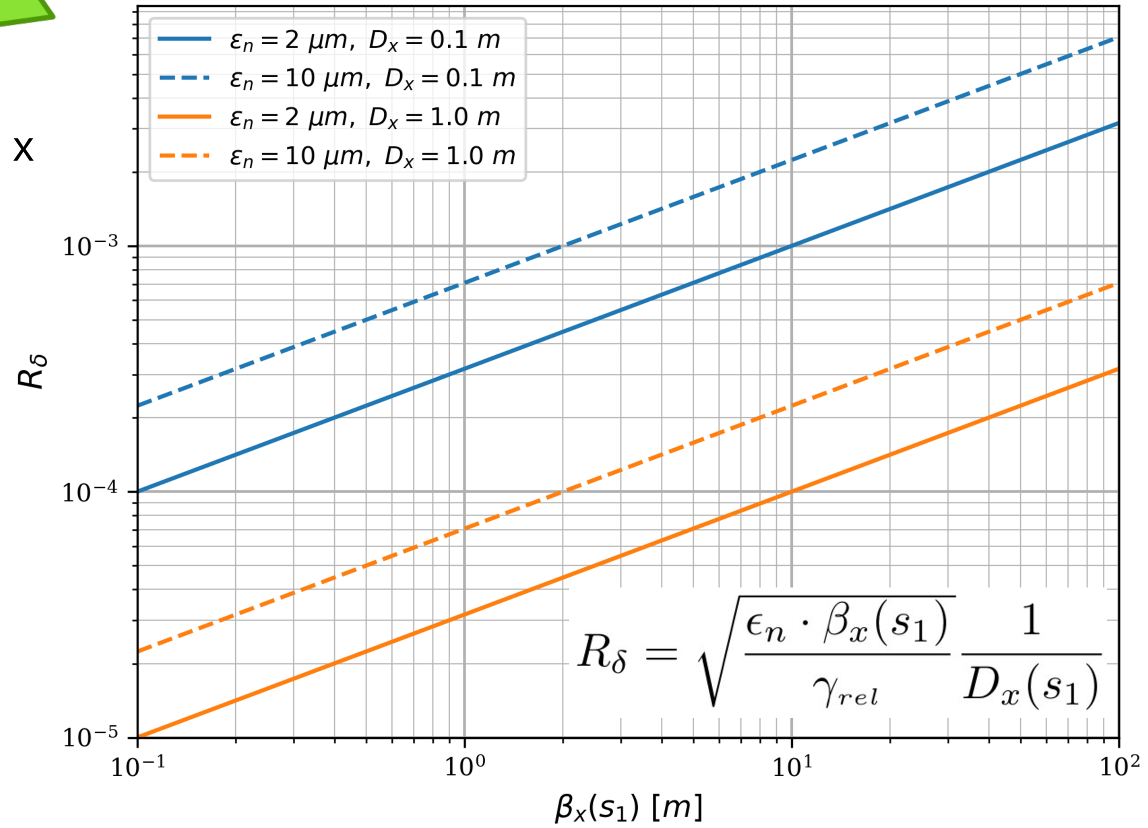
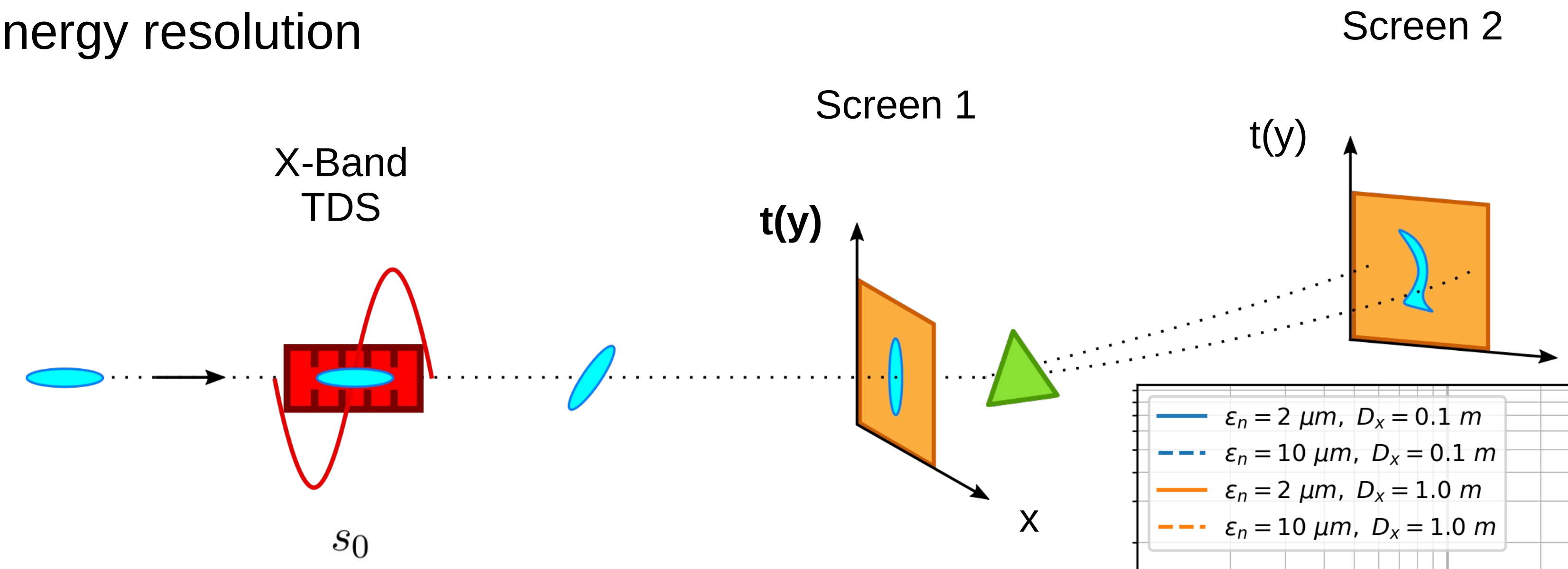


X-Band TDS Resolution

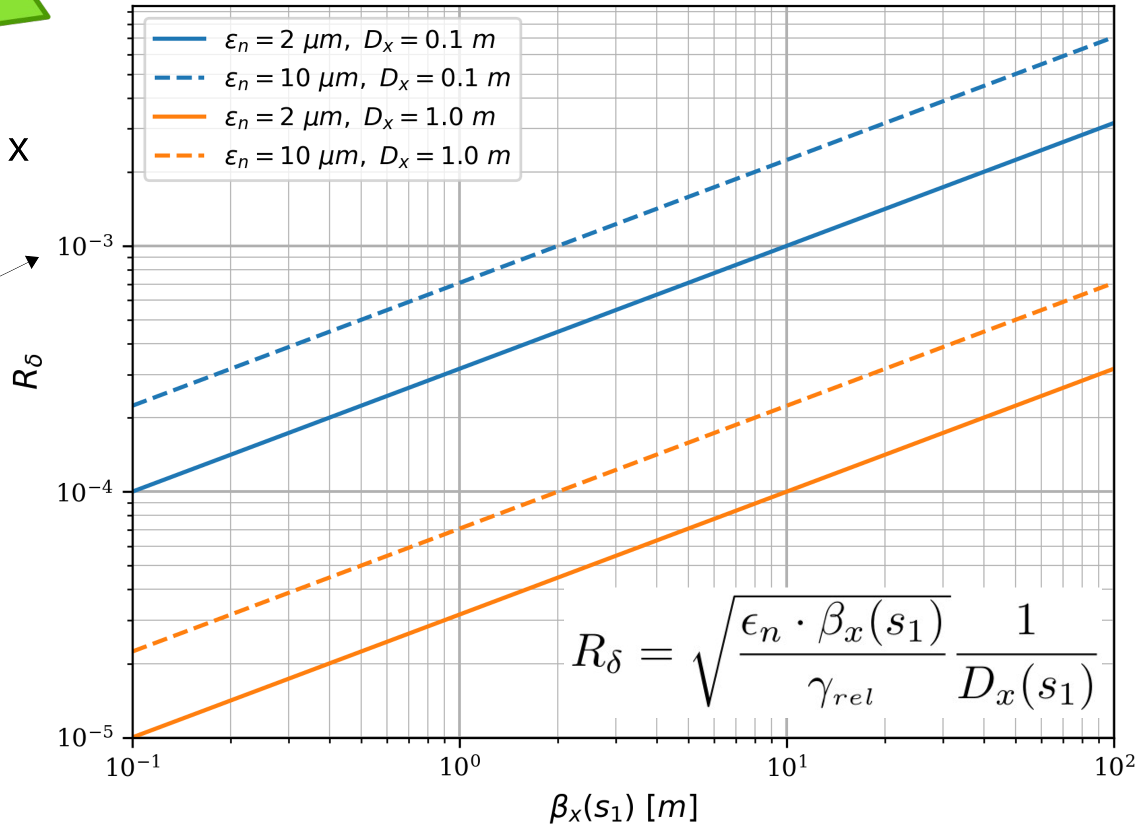
> **Real** energy resolution



uncorrelated energy spread

$$\sigma^2_{\Delta\delta} = K^2 \sigma^2_{y0}$$

$$K = \frac{eV_0 k}{pc}$$



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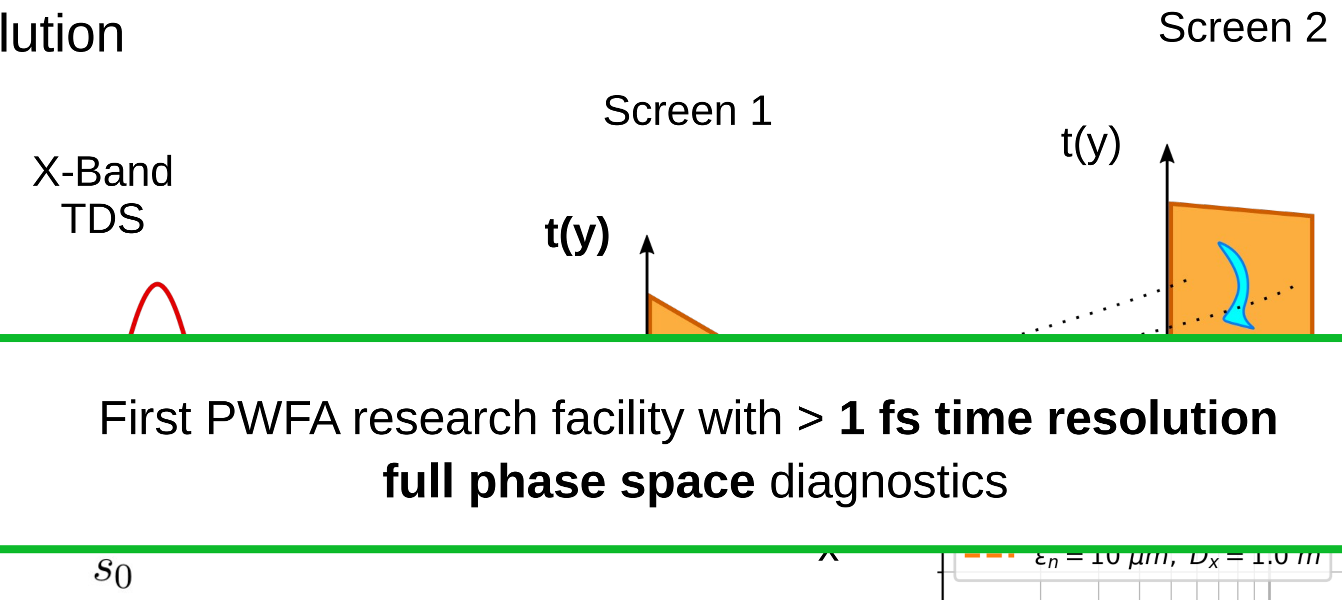

First PWFA research facility with > **1 fs time resolution**
full phase space diagnostics

uncorrelated energy spread

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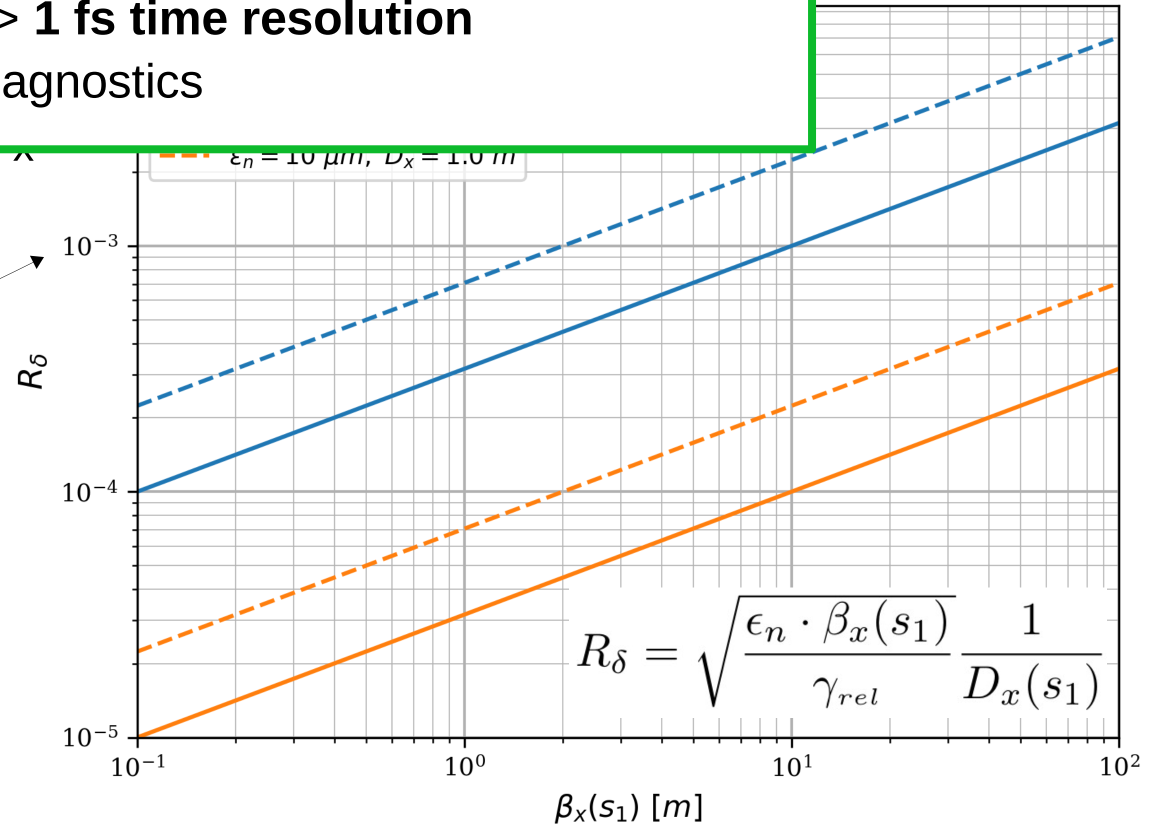
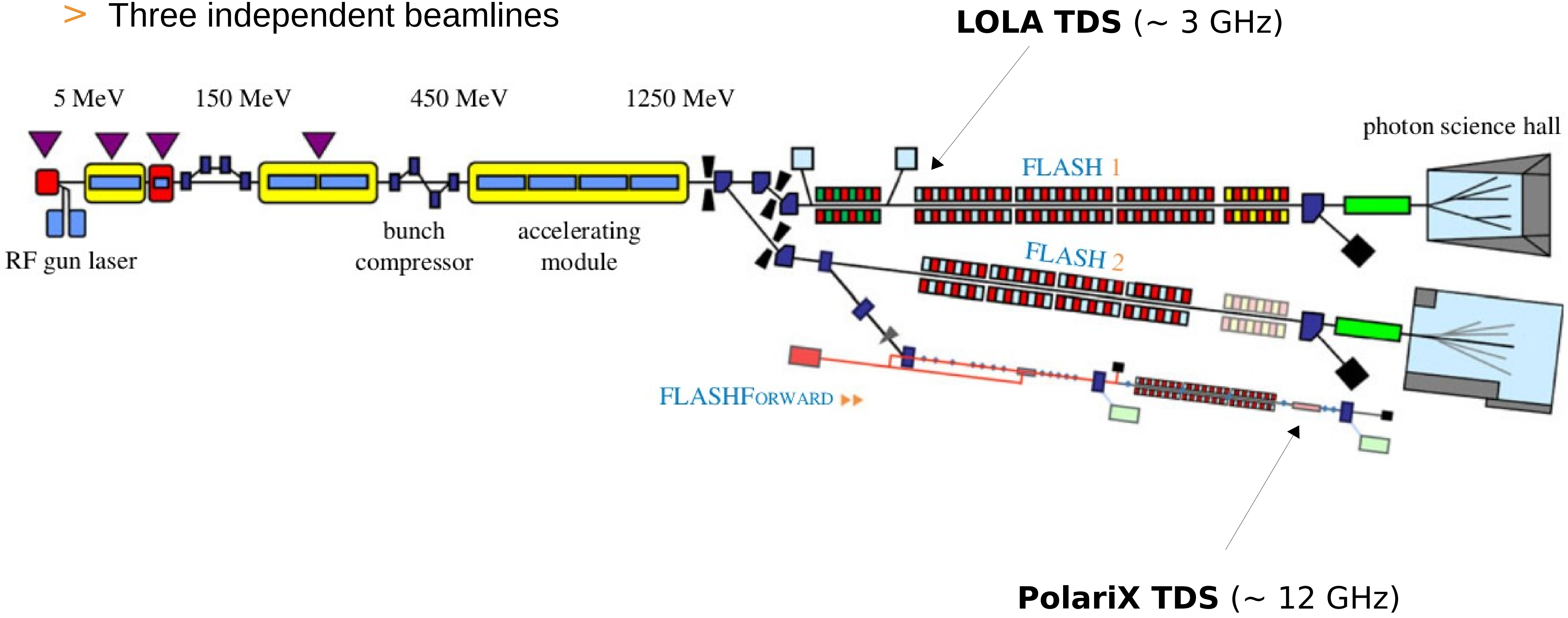


FLASH Beamline Layout

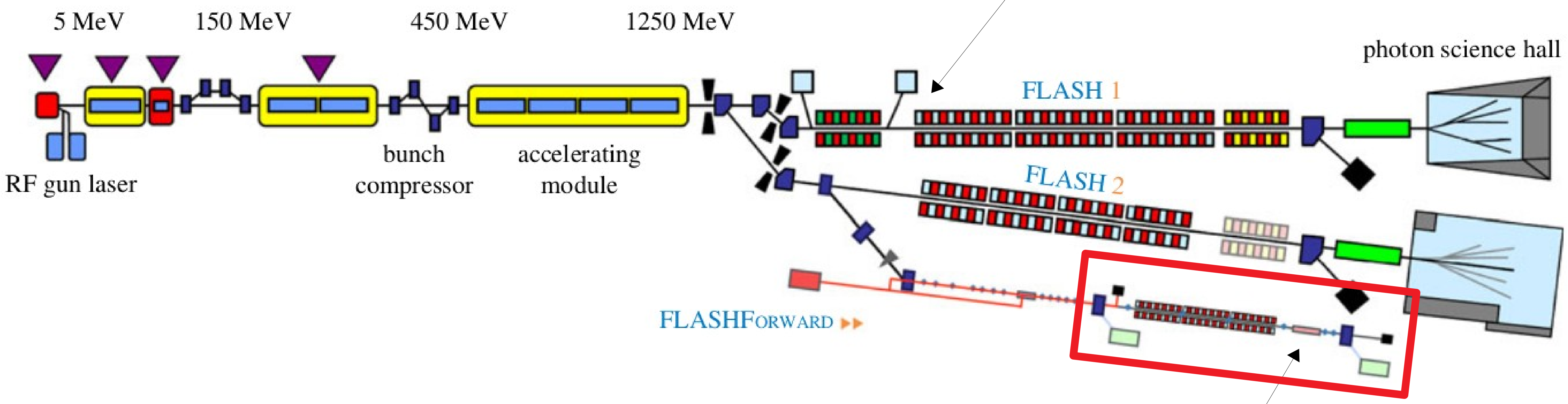
> Three independent beamlines



FLASH Beamline Layout

- Three independent beamlines

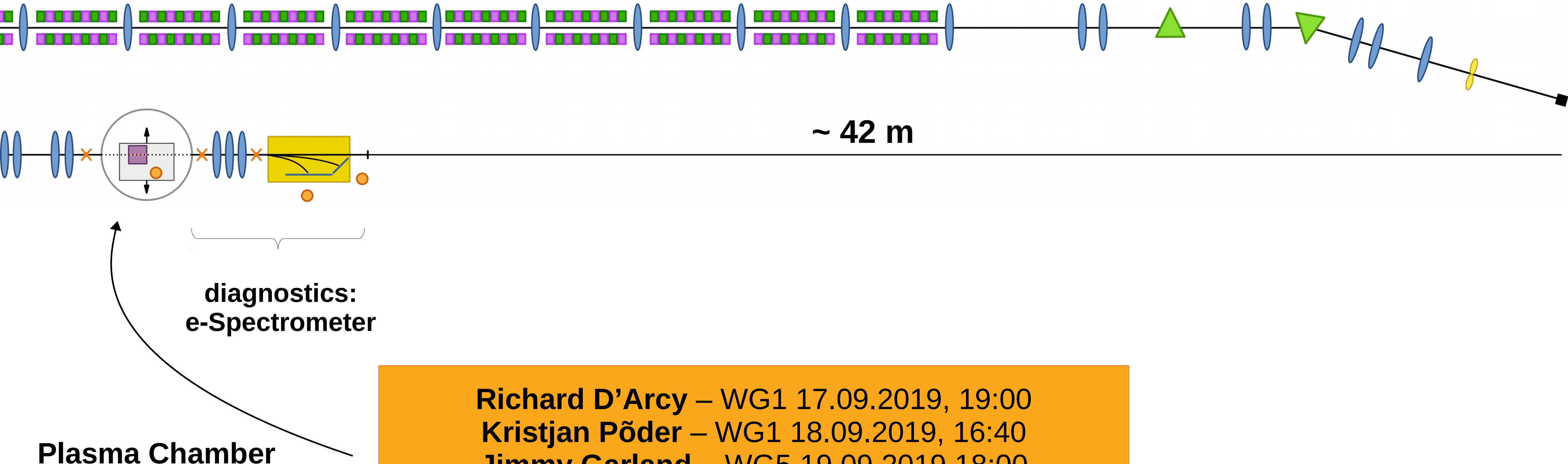
LOLA TDS (~ 3 GHz)



PolariX TDS (~ 12 GHz)

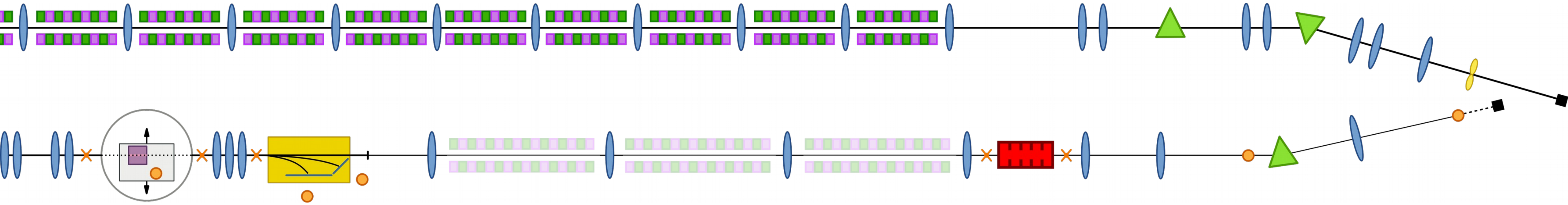
FLASHForward▸▸ BEAMLINE LAYOUT

> Post-plasma beamline layout



Richard D'Arcy – WG1 17.09.2019, 19:00
Kristjan Põder – WG1 18.09.2019, 16:40
Jimmy Garland – WG5 19.09.2019 18:00
Sarah Schröder – Plenary talk 20.09.2019 9:40

> Design constraints:



1) TDS position → **shared hardware with FLASH2** (minimise waveguide losses and also costs)
2) Before the TDS → **future installation of 3 undulators** for FEL generation
3) Before & after the TDS → **optimisation of time and energy resolution** with appropriate optics.

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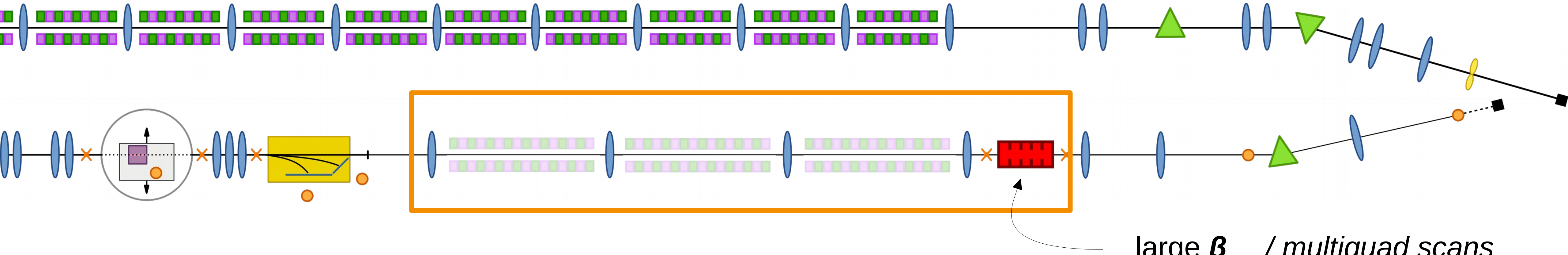

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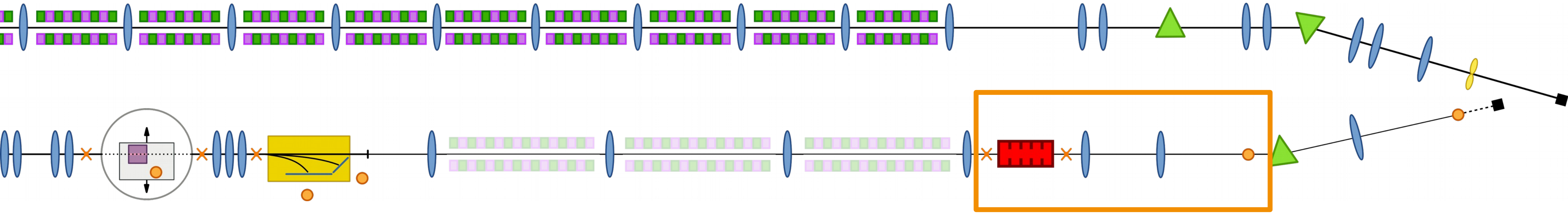

$\Delta\psi_{TDS \rightarrow SCR} = \pi / 2$

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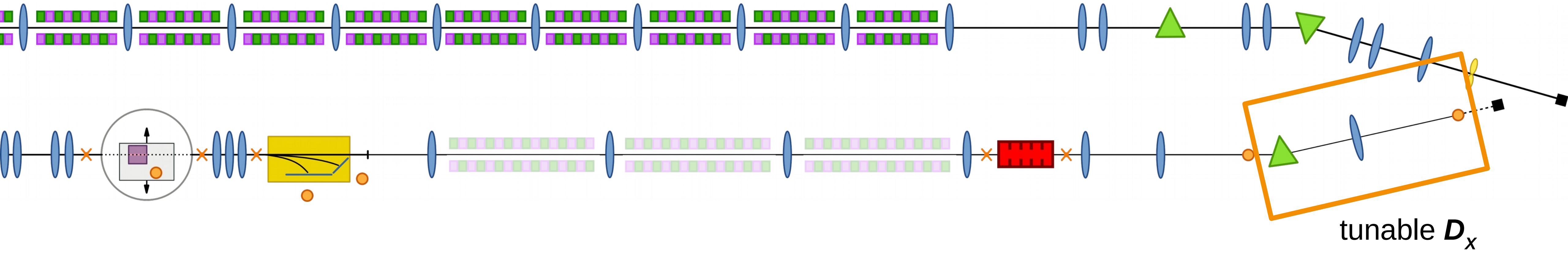

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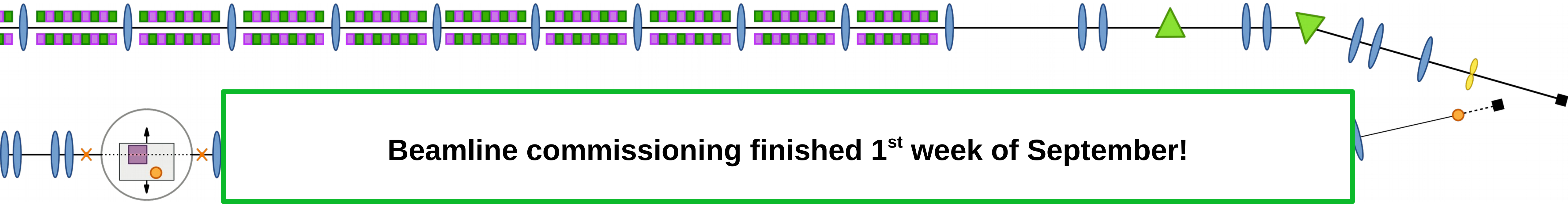

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X-Band TDS Commissioning (80 hours, 6–10.09.2019)

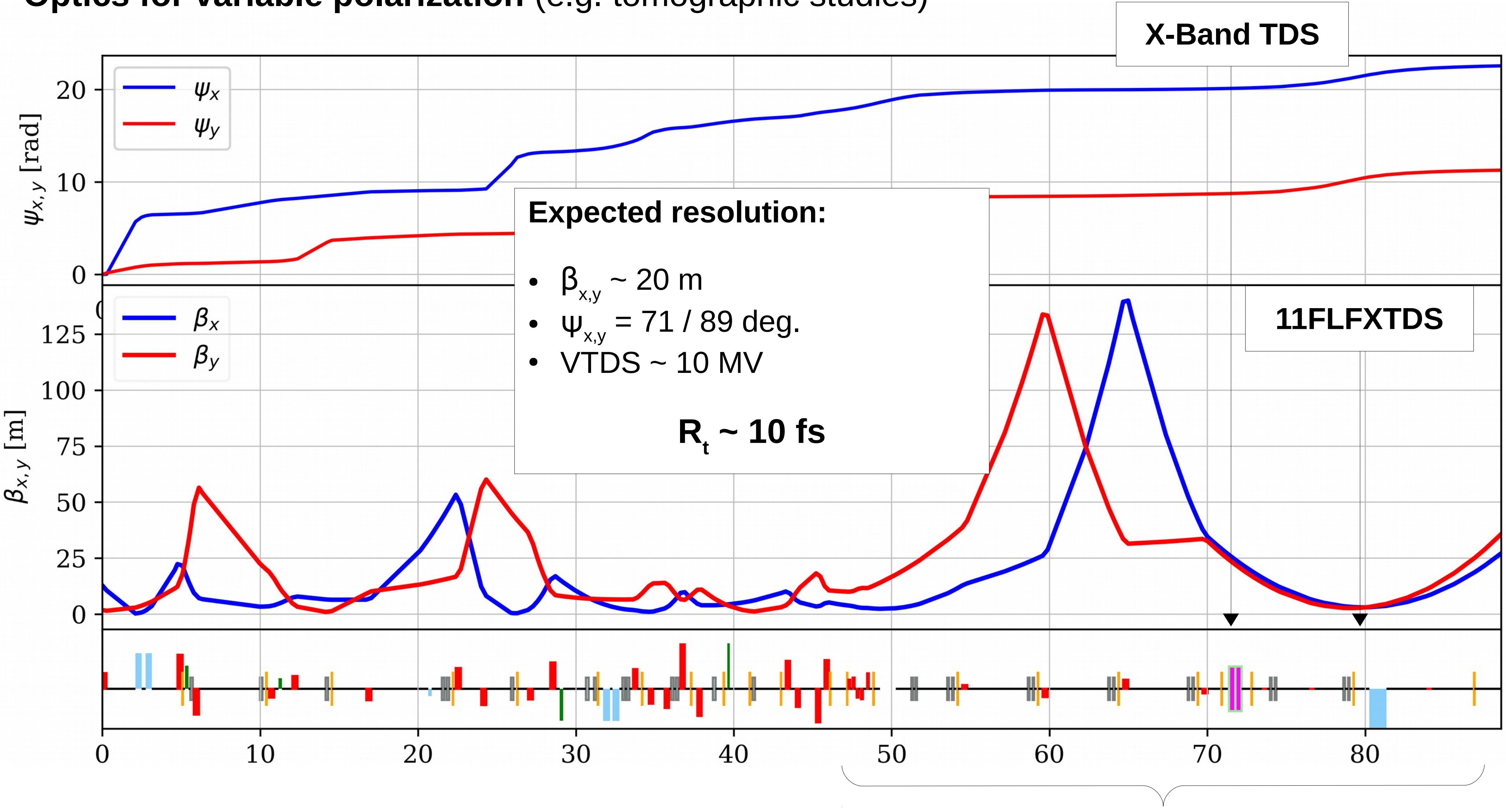
> **Goals**:

- Commission **LLRF system**
- 1st world wide demonstration of **variable polarization streaking**
- **Benchmark** the PolariX against the LOLA-TDS
- Take data for **tomographic reconstruction**
- Bonus: **slice emittance scan**

> **Bunch properties**:

- charge = **600 pC**
- energy = **1.1 GeV**
- normalized emittance ~ **2 µm**
- compression settings: MES / ~ 500 fs / **~ 200 fs** (~ linear chirp)

> **Optics for variable polarization** (e.g. tomographic studies)

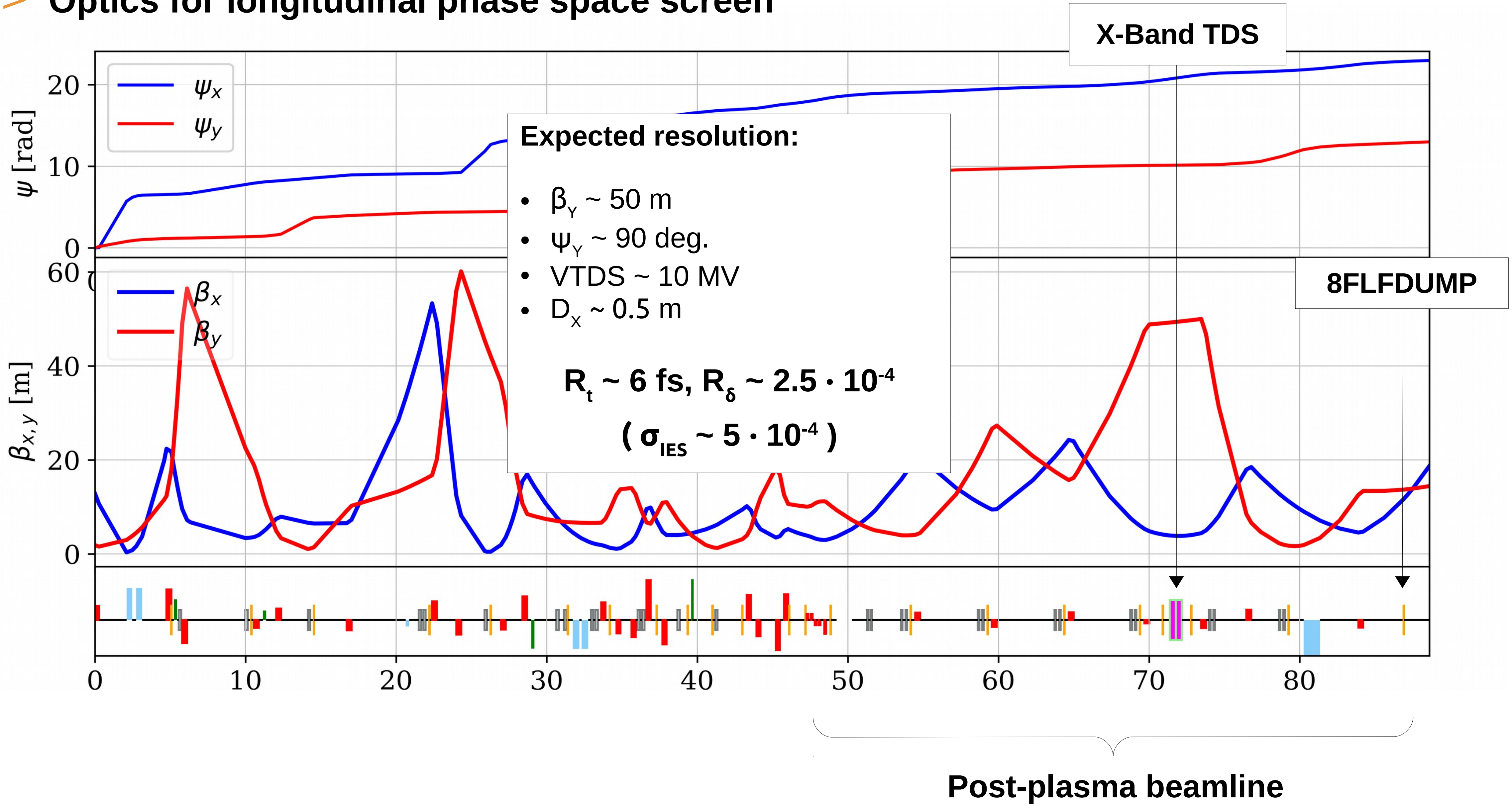


Expected resolution:

- $\beta_{x,y}$ ~ 20 m
- $\psi_{x,y}$ = 71 / 89 deg.
- VTDS ~ 10 MV

R_t ~ 10 fs

> Optics for longitudinal phase space screen



Expected resolution:

- β_Y ~ 50 m
- ψ_Y ~ 90 deg.
- VTDS ~ 10 MV
- D_X ~ 0.5 m

R_t ~ 6 fs, R_δ ~ $2.5 \cdot 10^{-4}$

(σ_{IES} ~ $5 \cdot 10^{-4}$)

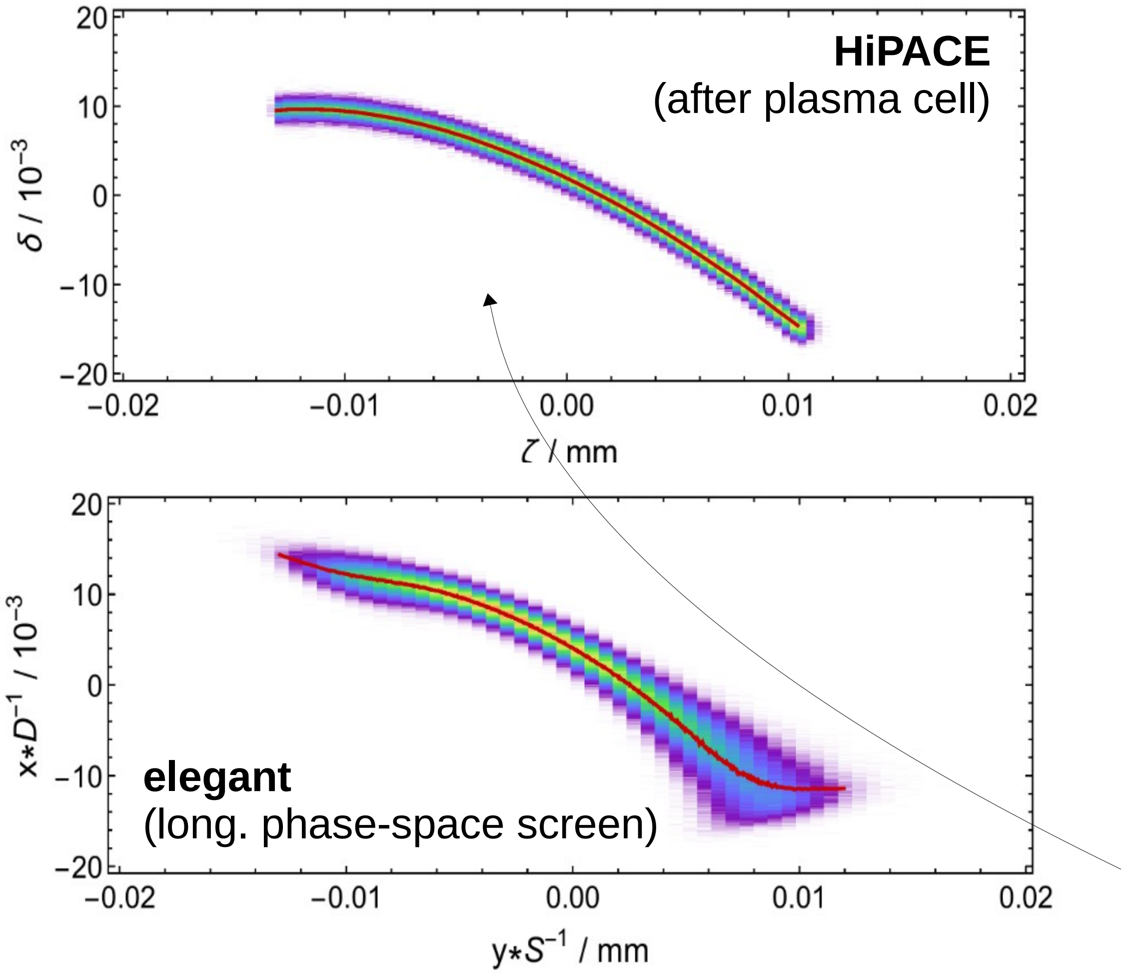
X-Band TDS Commissioning Summary

- LLRF works fine at its current max. power of ~ 6 MW
- Demonstrated variable streak polarization at full power in all streaking directions
- Achieved resolutions of < 10 fs without too much effort on optics optimizations
- Jitter has not been a critical issue
- Completed data taking for:
  - tomographic studies (Daniel Marx, DESY)
  - comparative studies between X-Band TDS and LOLA-TDS
  - slice emittance scan

} Data analysis ongoing

Simulations and Longitudinal Phase Space Reconstruction

Realistic case: **start-to-end simulations for externally injected witness bunch**



R. D'Arcy, A. Aschikhin, P. Gonzalez, J. Osterhoff, V. Libov,
Proc. of IPAC 2018, **TUPML017**

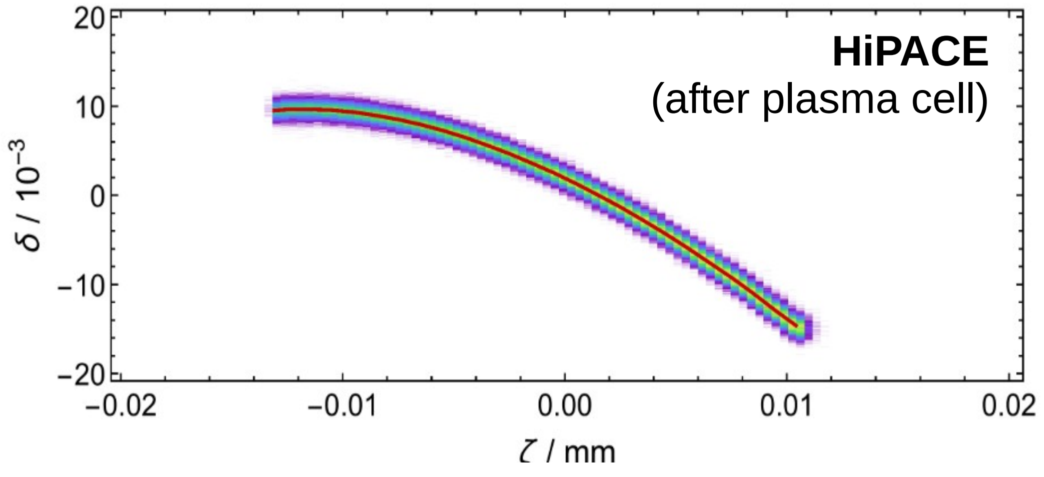
> Boundary conditions:
- scraped 1 GeV FLASH-type bunch
- linear chirp, energy spread ~ 0.5 %, ~ 200 fs
- plasma: L = 20cm, n_e = $5{\cdot}10^{16}$ cm^{-3} (β ~ 2 mm), 50 mm exponentially decreasing taper

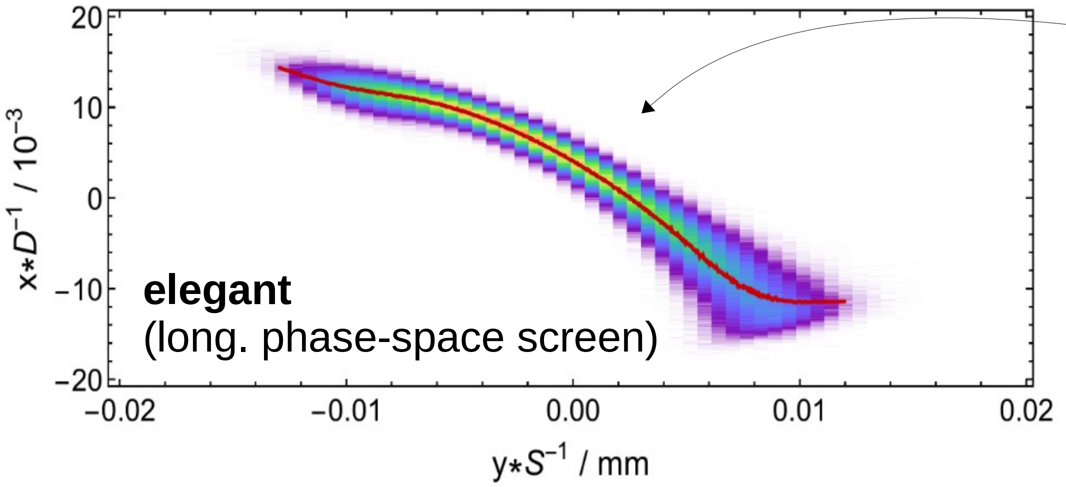
> Start to end scheme:
- Bunch generation → **ASTRA**
- Tracking → **elegant**
- Double bunch generation → **Geant4**
- Plasma → **HiPACE**

> Accelerated witness bunch
- acc. gradient ~ 2.6 GeV/m
- final energy ~ 1.5 GeV
- length ~ 20 fs, $\beta_{x,,y}$ ~ 20 mm, $\alpha_{x,y}$ ~ 0.1

Simulations and Longitudinal Phase Space Reconstruction

Realistic case: **start-to-end simulations for externally injected witness bunch**





> X-Band TDS parameters:
- $V = 27$ MV
- $R_t = 2.45$ fs, $R_\delta = 1.24 \cdot 10^{-4}$

> **Results:**
- degradation of the phase-space during propagation through the TDS due to:
  - induced energy spread / chirp
  - CSR effects
- **However, resolution is good enough to estimate the correct bunch length**

R. D'Arcy, A. Aschikhin, P. Gonzalez, J. Osterhoff, V. Libov,
Proc. of IPAC 2018, **TUPML017**

Summary and Outlook

- A PolariX TDS (variable polarization X-Band TDS) has been installed and successfully commissioned at FLASHForward
- Time resolutions below 10 fs have been easily achieved and the ability to streak at any directions has been demonstrated
- With this diagnostics tool, FLASHForward is the first PWFA facility in the world able to provide phase space information with an unprecedented time resolution on the 1 fs time scale
- In the present, preparations are ongoing for the upcomming beamtimes to perform diagnostics on PWFA electron bunches
- Studies are ongoing to further assess the adverse effects of induced energy spread, coherent synchrotron radiation, different sources of jitter and beam transport of PWFA electron bunches for both external and internal injection schemes

Thank you

Contact

DESY. Deutsches Elektronen-Synchrotron

www.desy.de

González Caminal, Pau
FLA – Linear Accelerator Technologies
pau.gonzalez@desy.de
+49 (0)40 8998 4960

X-BAND TDS RESOLUTION

> REAL ENERGY RESOLUTION: **INDUCED ENERGY SPREAD**

"Parasitic" longitudinal force depending on y:

$$F_x = 0$$
$$F_y = eE_0 \sin \Phi$$
$$F_z = eE_0 \cos \Phi \cdot ky$$

$$\Delta\delta = \frac{c\Delta p}{cp} \approx \frac{\Delta p_z}{cp} = K y_0 + \frac{1}{2} K L y_0' \pm \frac{1}{6} K^2 L z$$, with $K = \frac{eV_0 k}{pc}$

1st and 2nd moments

- **uncorrelated energy spread** ($\sigma_{IES} = \sigma_{\Delta\delta}$):

$$\sigma_{\Delta\delta}^2 = K^2 \sigma_{y0}^2 + \left(\frac{1}{2} K L\right)^2 \sigma_{y'0}^2 + \left(\pm \frac{1}{6} K^2 L\right)^2 \sigma_z^2$$

- **linear energy correlation along the bunch**:

$$\langle \Delta\delta \rangle = K \langle y_0 \rangle + \frac{1}{2} K L \langle y_0' \rangle \pm \frac{1}{6} K^2 L \langle z \rangle$$

X-Band TDS Resolution

> Real Energy Resolution: **Induced Energy Spread**

“Parasitic” longitudinal force depending on y:

$$F_x = 0$$
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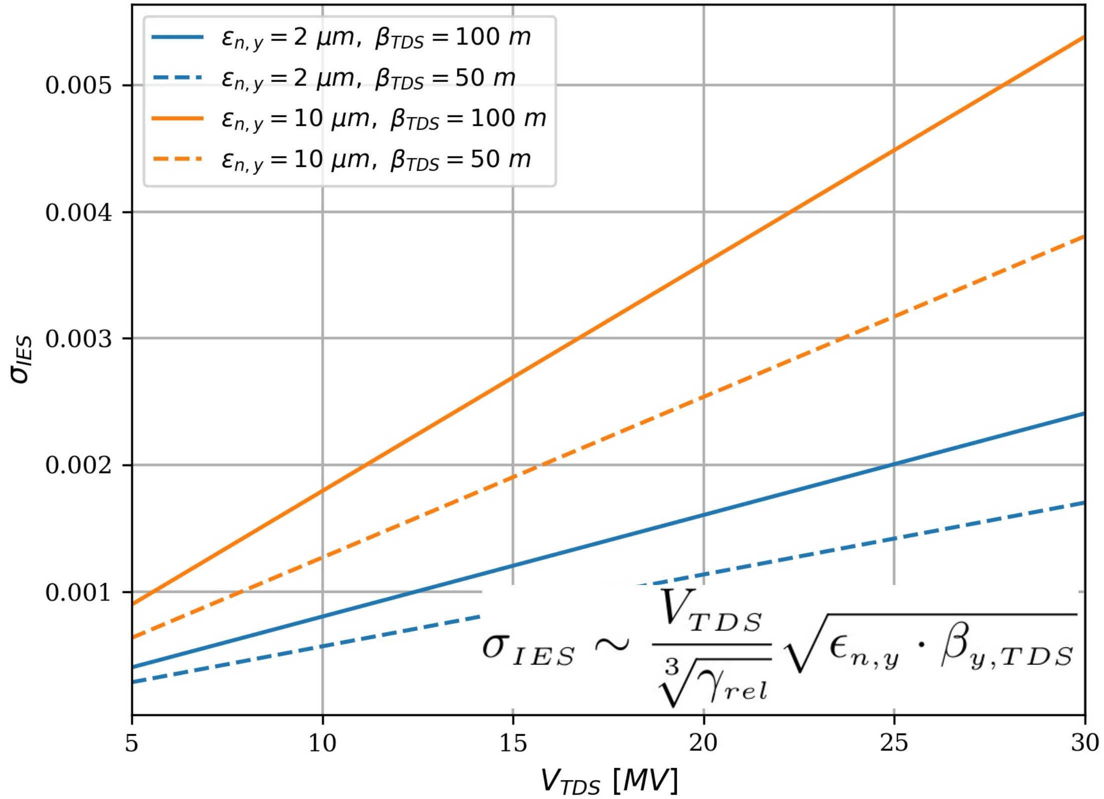
1st and 2nd moments

- **uncorrelated energy spread** ($\sigma_{IES} = \sigma_{\Delta\delta}$):

$$\sigma^2_{\Delta\delta} = K^2 \sigma^2_{y0}$$

$\gamma \ll 1,\ \sigma_z \sim 0.0$



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