PolariX TDS Project

Polarisable X-band Transverse Deflection Structure development

Richard D'Arcy (on behalf of the PolariX collaboration)

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

MT ARD

DESY.

Credits and contributions

Thanks to the many people who have and continue to contribute to this project!

- **DESY**

  R. Assmann, B. Beutner, J. Branlard, F. Christie, B. Conrad, M.K. Czwalinna, R. D’Arcy, W. Decking, U. Dorda, M. Foese, P. Gonzalez Caminal, J. Herrmann, M. Hoffmann, M. Hüning, R. Jonas, K. Klose, O. Krebs, G. Kube, S. Lederer, F. Ludwig, F. Marutzky, D. Marx, J. Osterhoff, I. Pepperkorn, S. Pfeiffer, F. Poblotzki, M. Reukauff, J. Roensch-Schulenberg, J. Rothenburg, G. Tews, H. Schlarb, M. Scholz, S. Schreiber, 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. Ganter, T. Kleeb, F. Marcellini, M. Pedrozzi, E. Prat, S. Reiche, K. Rolli, R. Zennaro

- **CERN**

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

Why do we want this device?

Scientific motivation for this technological advance

Goal:

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

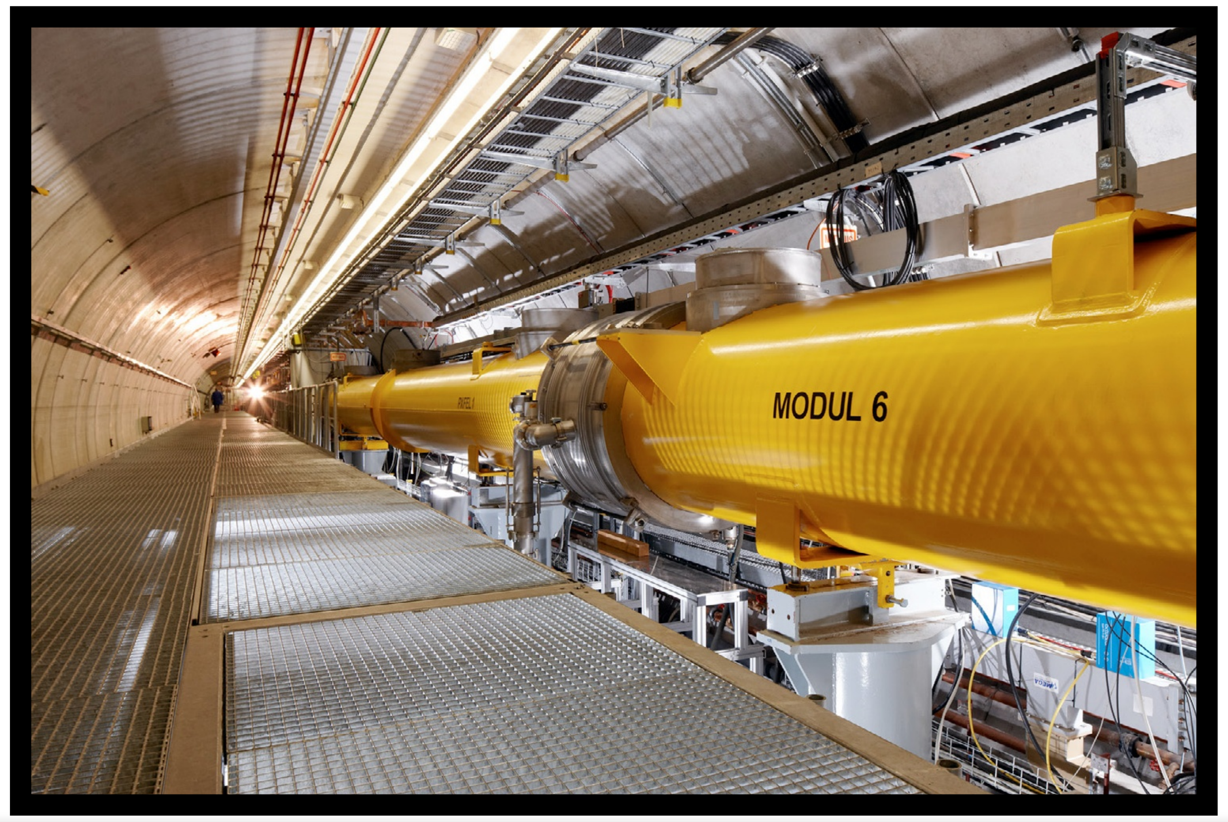
> Femtosecond-level temporal resolution are required for optimisation of ultra-short bunches

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

Transverse Deflection Structure (TDS)

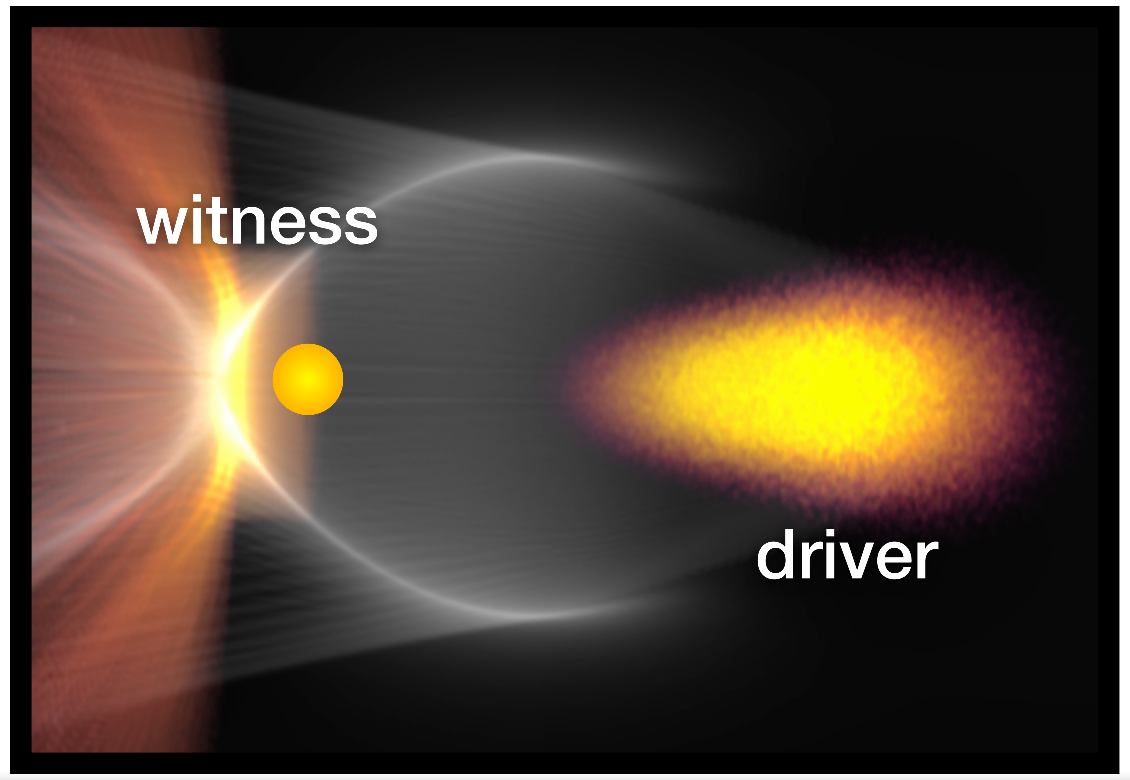
High-frequency (X-band) regime

Variable polarisation streaking



Free-electron Lasers e.g. FLASH

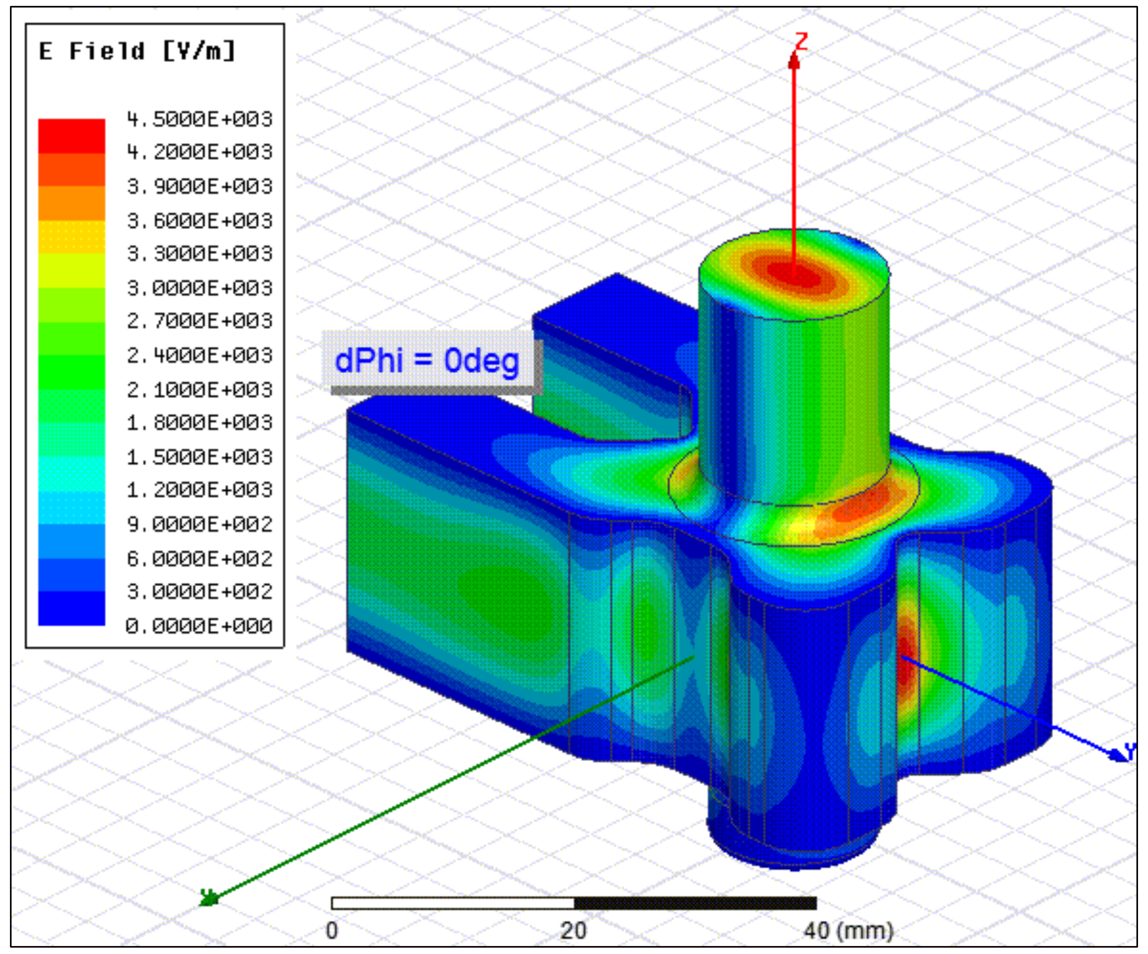
Accelerators on a chip



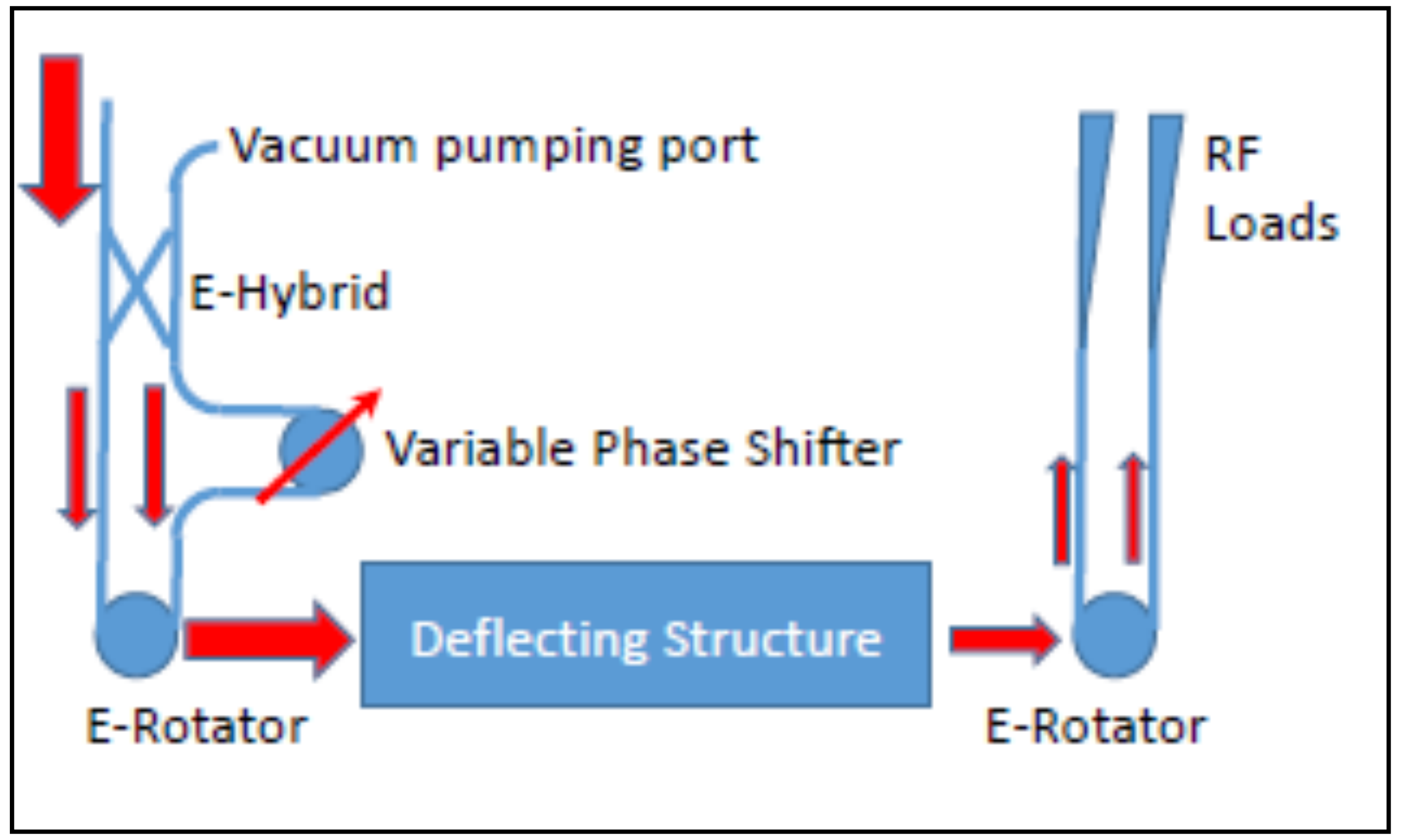
Plasma-based accelerators

New generation of variable streaking temporal diagnostic

PolariX TDS = Polarisable X-band Transverse Deflection Structure



Variable-polarisation circular TE11-mode phase launcher

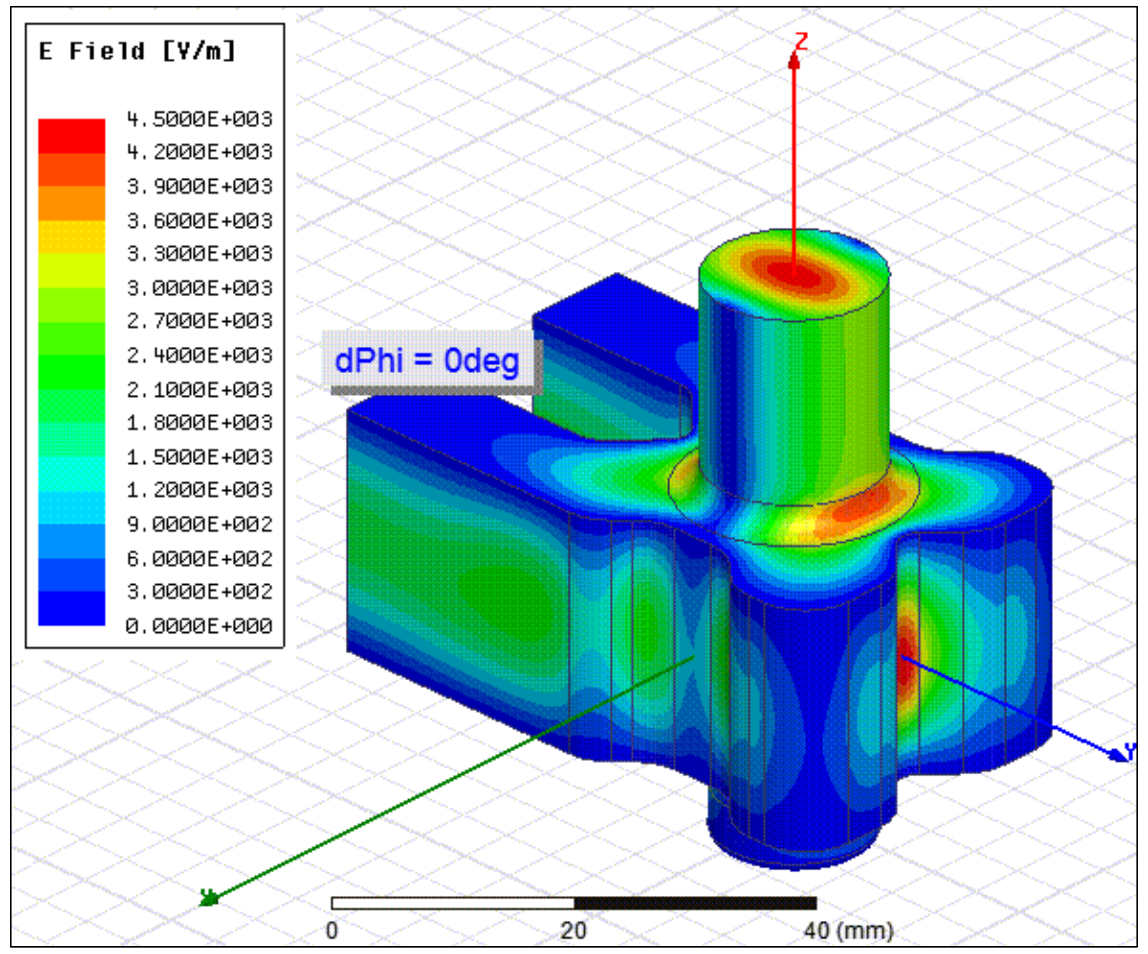


Phase difference between 1st and 2nd port:

- 0 degree ➞ vertically streaking field
- 180 degree ➞ horizontally streaking field

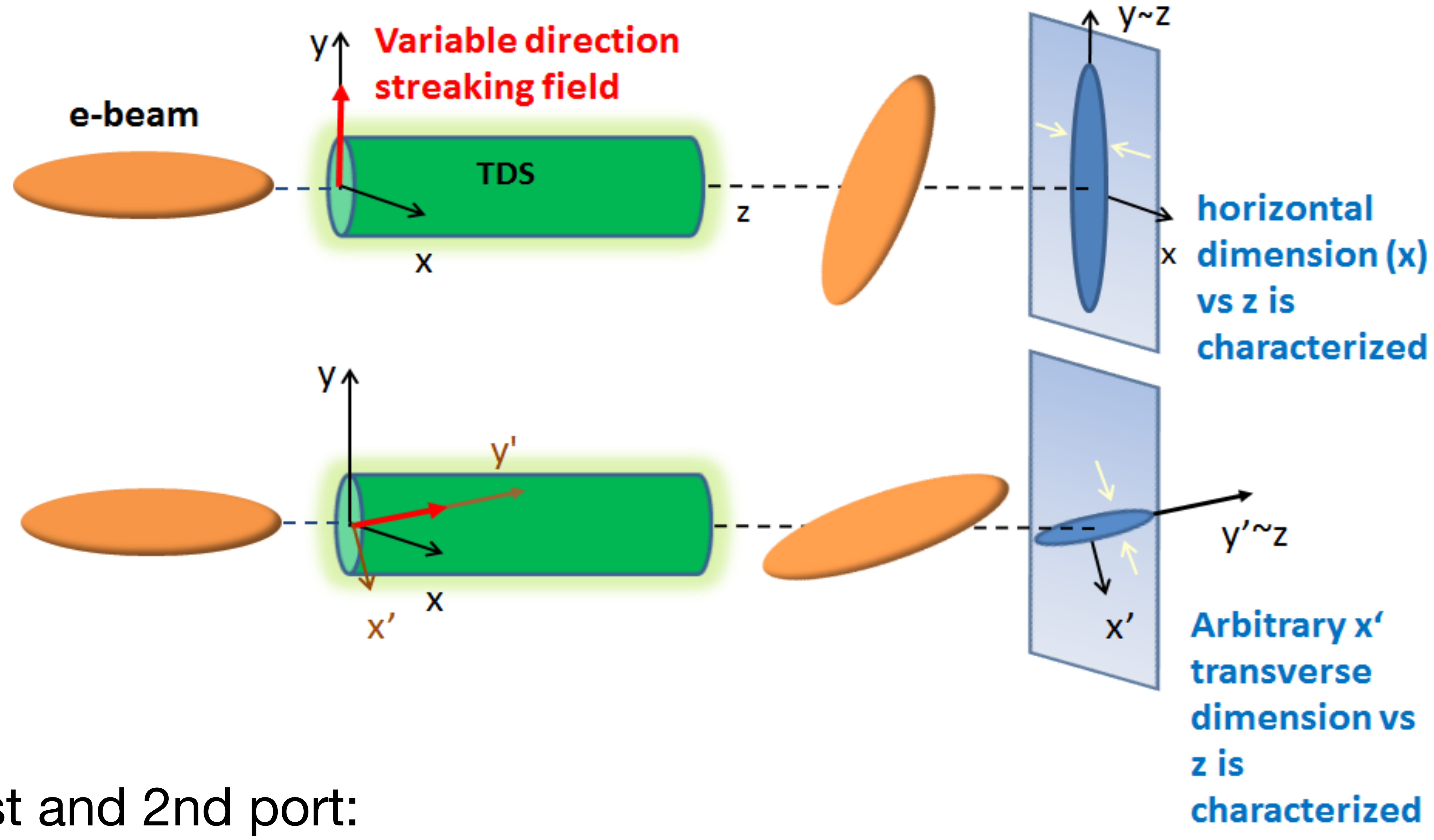
New generation of variable streaking temporal diagnostic

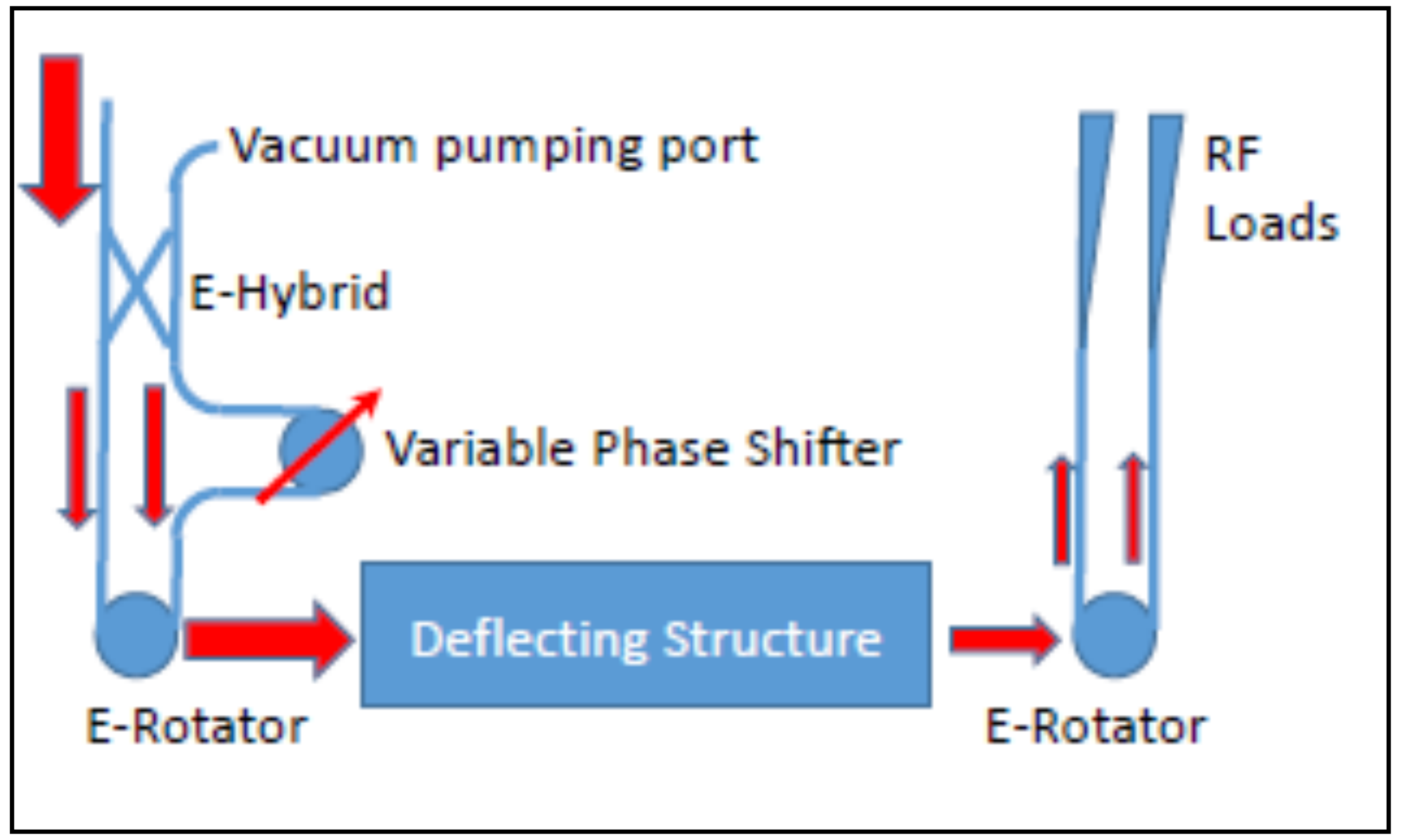
PolariX TDS = Polarisable X-band Transverse Deflection Structure



Variable polarisation circular TE11-mode phase launcher

Enables the characterisation of slice properties along an arbitrary x' axis





Phase difference between 1st and 2nd port:

0 degree → vertically streaking field

180 degree → horizontally streaking field

Interest in this technology from many facilities

The varied experimental utilisation results in a wide parameter range

- Experiments participating in the project:
  - **FLASHFORWARD▸▸** (DESY) : fs-longitudinal diagnostics of driver/witness beams used in plasma-wakefield acceleration
  - **FLASH2** (DESY) : online longitudinal measurement with fs resolution of electron bunches for optimising FEL process
  - **SINBAD** (DESY): sub-fs longitudinal characterisation of ultra-short electron bunches
  - **ATHOS** (beamline at SwissFEL, PSI): optimisation of the FEL process
- ***EuXFEL** also a part of the collaboration but without financial commitment to structure purchase*

A brief history of the project

Design of unique polarisation components

- 2016
  - Variable polarisation concept proposed by A. Grudiev (CERN)
- 2017
  - Collaboration partners established
  - Device specifications defined by experimental needs
- 2018
  - Collaboration Agreement between partners signed
  - Mechanical design complete
- 2019
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  - First experiments with beam

CLIC – Note – 1067

DESIGN OF COMPACT HIGH POWER RF COMPONENTS AT X-BAND

Alexej GRUDIEV
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Abstract

In this note, designs of compact high power X-band RF components are presented. Their scaling to C-and S-band is straightforward and in many case could solve a problem of size encountered in previous designs.

Variable polarization circular waveguide TE11 mode launcher

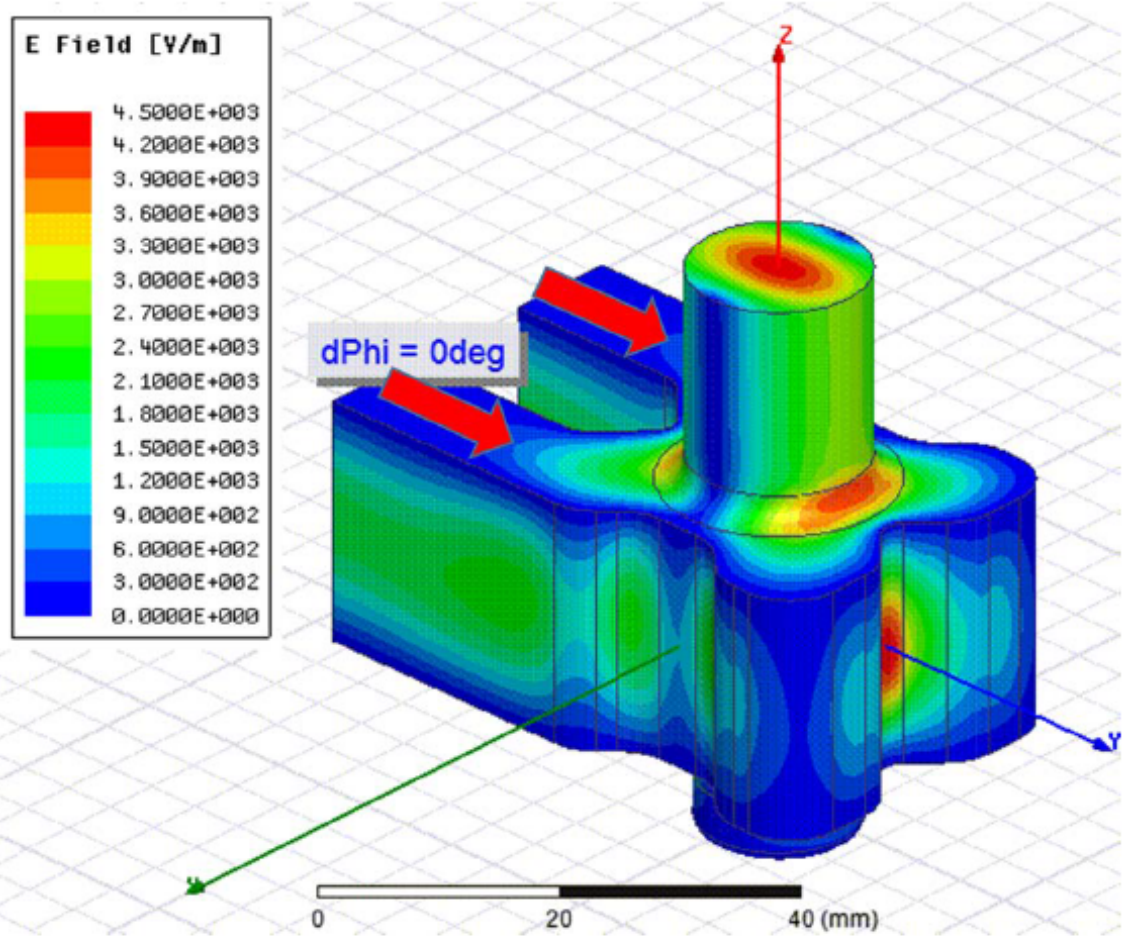

Fig 16. E-rotator as a linear polarized mode launcher.

Another use of the E-rotator is proposed in the following section. As demonstrated in Fig 5, if power is injected from port 1, a circular polarized mode is launched in port 3. If it is injected from port 2, a circular polarized mode rotating in opposite direction is launched in port 3. Injecting the same

A brief history of the project

Experimental demands define the cavity design

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X-BAND TDS PROJECT

B. Marchetti*, R. Assmann, B. Beutner, J. Branlard, F. Christie, R. D' Arcy, W. Decking, U. Dorda, J. Herrmann, M. Hoffmann, M. Huening, O. Krebs, G. Kube, S. Lederer, F. Ludwig, F. Marutzky, D. Marx, J. Osterhoff, I. Peperkorn, S. Pfeiffer, F. Poblotzki, J. Roensch-Schulenburg, J. Rothenburg, H. Schlarb, M. Scholz, S. Schreiber, M. Vogt, A. de Z. Wagner, T. Wilksen, K. Wittenburg
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DESY and PSI. We comment on the feasibility of the production of a prototype of such a device based on tolerances evaluations. Finally we introduce novel applications of the variable polarization TDS for e-beam diagnostics.

E-BEAM PARAMETERS

Several experiments at DESY (FLASH2, FLASHForward, SINBAD) and PSI (ATHOS at SwissFEL) are interested in the utilization of high gradient X-band TDS systems for high resolution longitudinal diagnostics. In this section we will briefly introduce the different experiments and highlight their needs.

FLASHForward

The FLASHForward project [7] is an innovative plasma-wakefield acceleration experiment, aiming to accelerate electron beams to GeV energies over a few centimeters of ionized gas. These accelerated beams must be of sufficient quality to demonstrate free-electron laser gain; achievable only through rigorous analysis of both the drive- and accelerated-beam's longitudinal phase space. The pulse duration of these accelerated beams is typically in the few femtosecond range, and thus difficult to resolve with traditional diagnostic methods. In order to longitudinally resolve these extremely short bunch lengths it is necessary to utilize the properties of such an X-band transverse RF deflector with high frequency and power, mapping longitudinal onto transverse coordinates.

FLASH2

At FLASH1 [8], the direct measurement of the longitudinal phase space with a deflecting RF structure has been proven to be of uttermost importance to establish femtosecond scale photon pulses [9, 10]. The installation of such a transverse deflecting cavity is planned also at FLASH2 [11]. Its combination with an existing dipole as a spectrometer will allow exploitation of the full longitudinal phase space and to optimize longitudinal bunch parameters for SASE and seeding processes. In contrast to FLASH1, the TDS at FLASH2 will be placed downstream of the undulators (see Fig.2). In such a configuration, the lasing part of the electron bunch can directly be measured and thus provides an estimate of the photon pulse duration as well. The experiment aims for a temporal resolution of less than 10 fs.

Figure 2: Exit of the SASE undulator section at FLASH2. Two TDS cavities are foreseen to be installed in the free space downstream the undulator.

SINBAD

The SINBAD (Short INnovative Bunches and Accelerators at DESY) facility [12] will be dedicated to accelerator research and development, building upon DESY's recent investment in this area in the framework of the Helmholtz ARD programme. It will be used for experiments in Plasma Wakefield Acceleration, dielectric accelerating structures and other novel accelerators. A 100-MeV electron linac, ARES, which will be constructed in phases from 2017 to 2019, will be able to provide very short (sub-fs) electron bunches with low charge (sub-pC), as required for plasma and dielectric experiments. The planned X-band TDS with variable polarization will make the characterization of ARES bunches at the end of the linac possible, which is essential for these experiments.

ATHOS at SwissFEL

The SwissFEL project [13], under commissioning at the Paul Scherrer Institut (PSI), will produce FEL radiation for soft X-rays, at the Athos beamline and hard X-rays, at the Aramis beamline, with pulse durations ranging from a few to several tens of femtoseconds. The goal of Athos is to provide a source of extremely brightness and short X-ray pulses. In order to increase performances in terms of photon beam brightness and bandwidth several innovative lasing schemes and technical developments for some key components are underway. As a diagnostic tool, two TDSs will be installed downstream of the undulators of the Athos beamline, which will allow to indirect measurement of the X-Ray pulse length by analyzing the induced energy spread on the electron bunch due to the FEL process. Furthermore, thanks to the variable polarization of the TDS it will be possible to perform a complete characterization of the 6D phase space by means of measurements of bunch length, energy and transverse slice emittances (vertical and horizontal).

Table 1 summarizes the e-bunch characteristics, the spatial constraints and the specifications for the TDS design for all the experiments listed above. It can be noticed that a common mechanical design for the structure is possible by tuning the temperature of the cavity in order to adjust its resonance frequency.

Table 1: TDS Specifications

	SINBAD	FLASH2	FLASHForward	ATHOS SwissFEL
Charge [pC]	0.5-30	20-1000	20-500 (driver) 10-250 (witness)	10-200
Norm. RMS Emit. [μm]	0.1-1	0.4-3	2.0-5.0 (driver) 0.1-1.0 (witness)	0.1-0.3
RMS Bunch Length [fs]	0.2-10	<3-200	50-500 (driver) 1-10 (witness)	2-30
β Function at TDS [m]	10-50	7-20	50-200	50
Beam Energy [MeV]	80-200	400-1400	500-2500	2900-3400
Rep. Rate [Hz]	10-50	10	10	100
TDS Voltage [MV]	25-40	30-45	25-30	30-60
N.TDS	2	2	1	2
Max.Length [m]	3	<1.92	<2	4
TDS Iris [mm]	4	4	4	4
TDS Frequency [MHz]	11991.6	11988.8	11988.8	11995.2
Temperature Range[°C]	48	62	62	25-35

A brief history of the project

Collaboration agreement and prototype mechanical design

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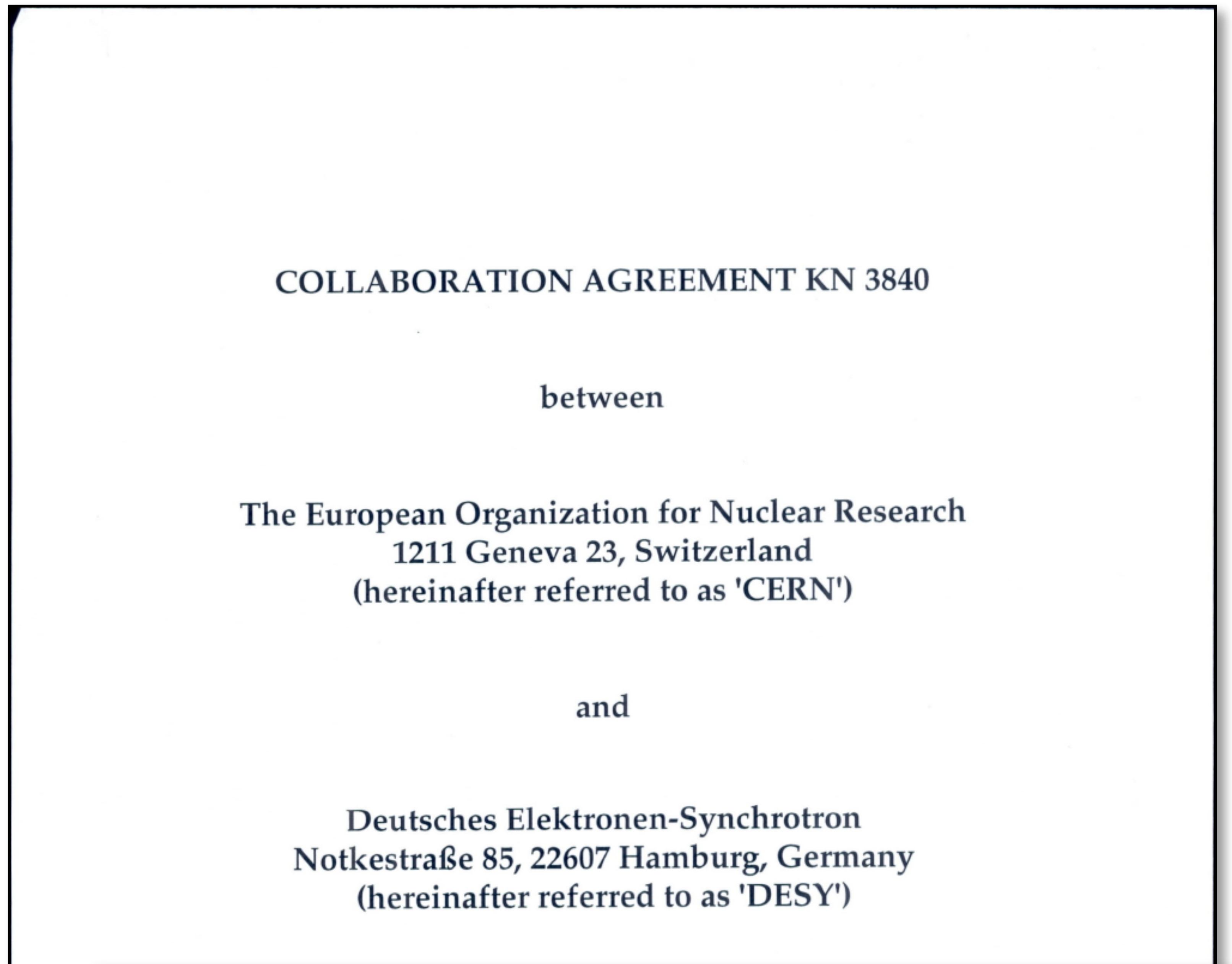
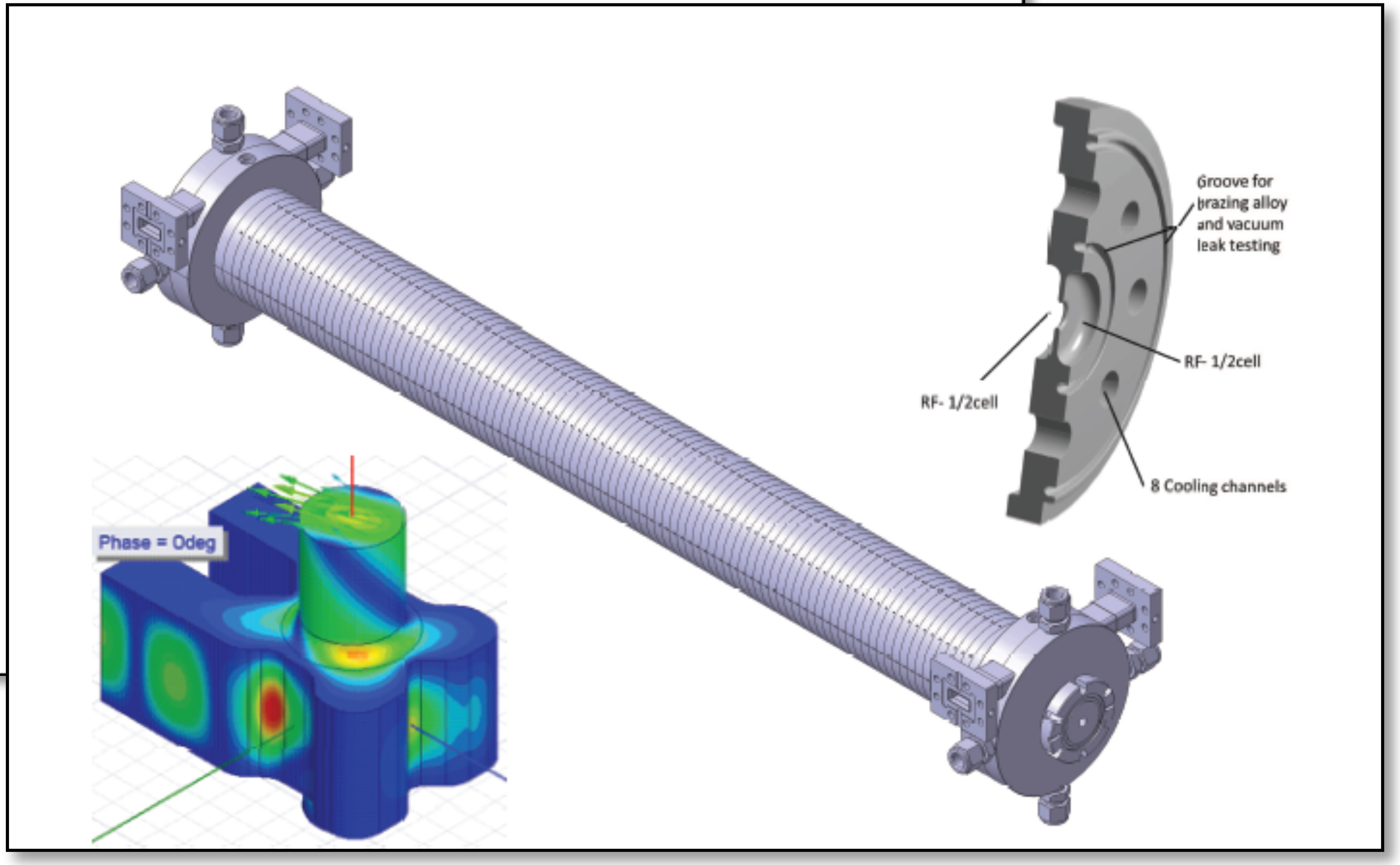

COLLABORATION AGREEMENT KN 3840

between

The European Organization for Nuclear Research
1211 Geneva 23, Switzerland
(hereinafter referred to as 'CERN')

and

Deutsches Elektronen-Synchrotron
Notkestraße 85, 22607 Hamburg, Germany
(hereinafter referred to as 'DESY')



A brief history of the project

Machining of the prototype and RF conditioning

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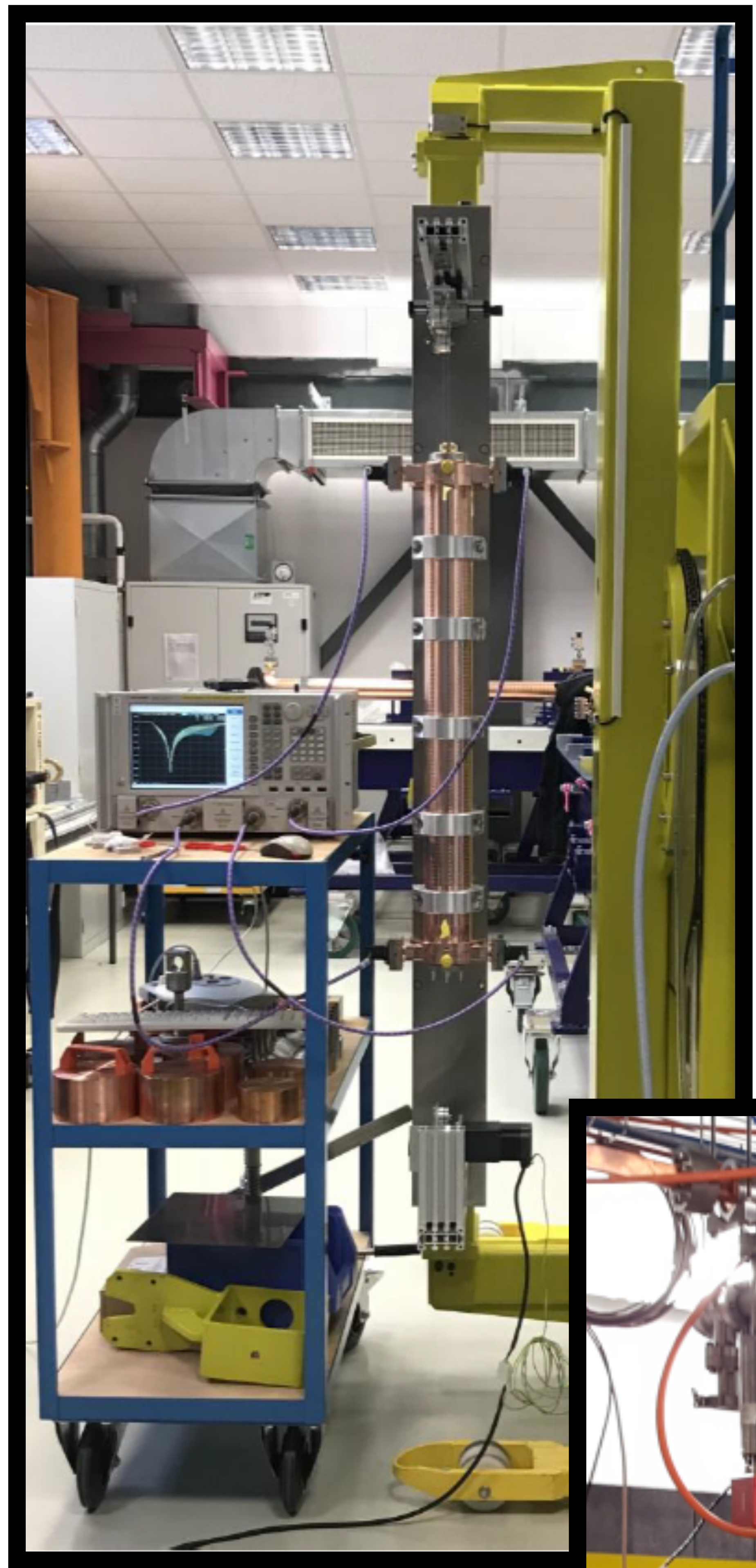
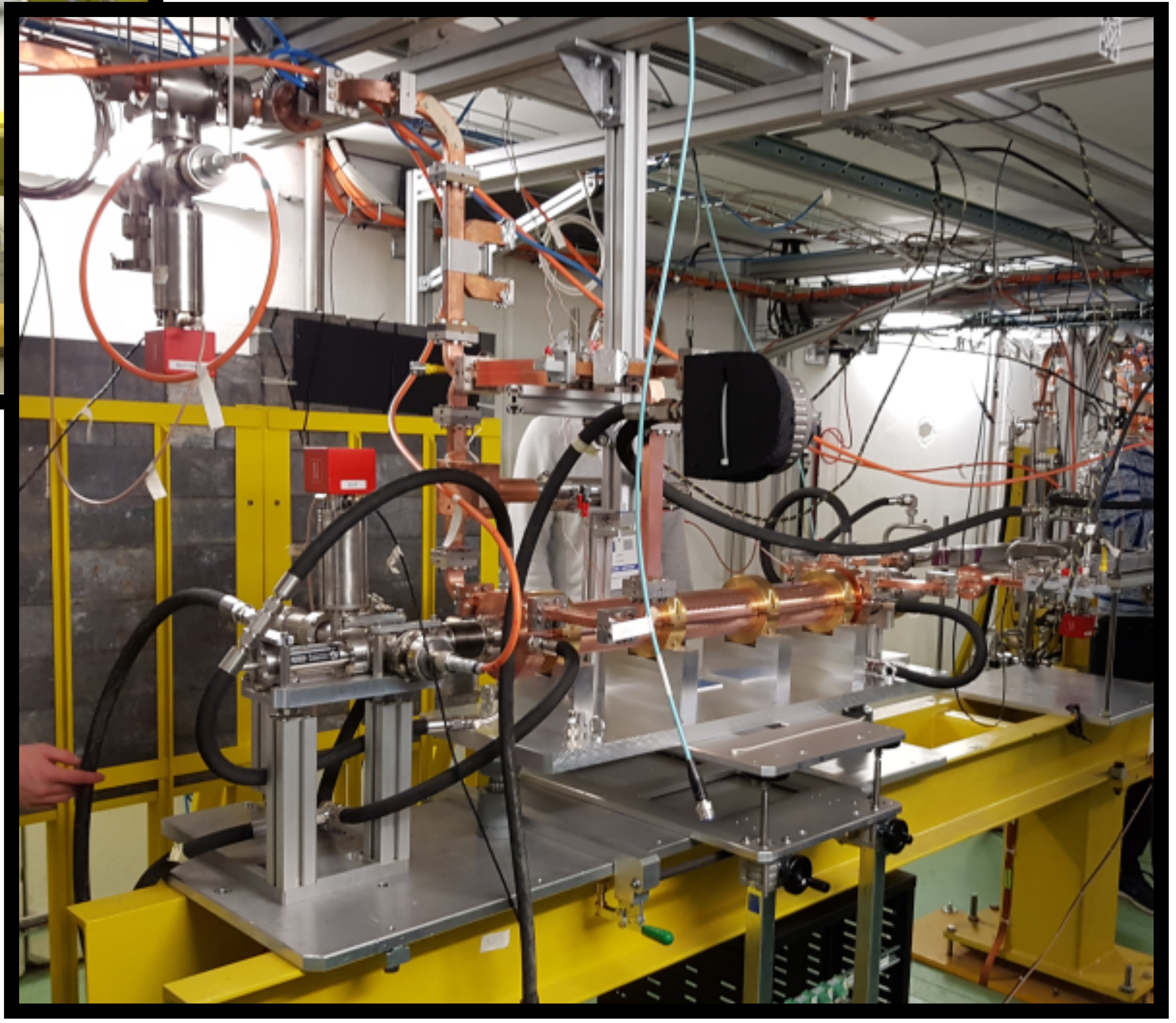


Bead-pull measurement at PSI



High power conditioning at CERN

A brief history of the project

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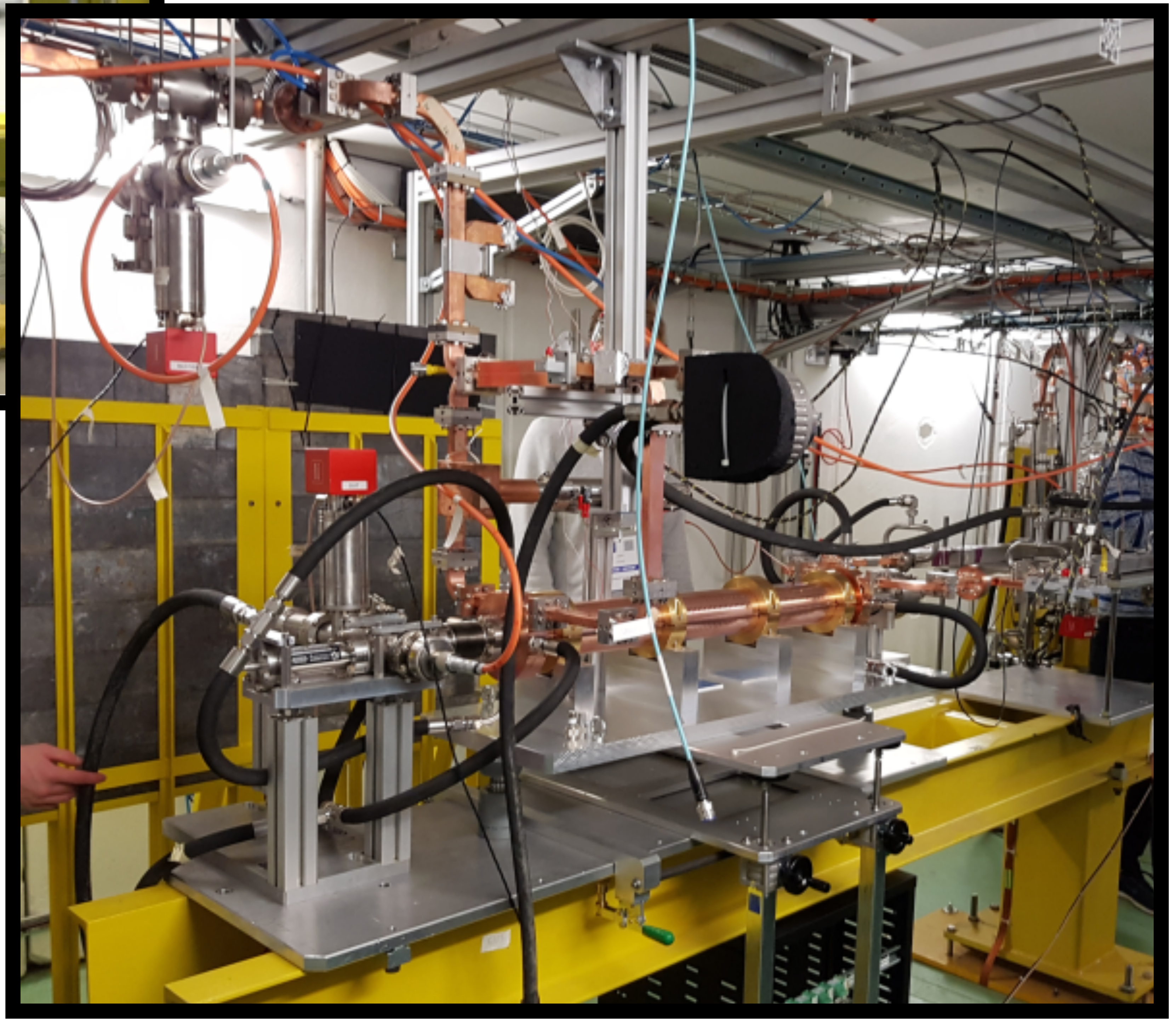
  - **First experiments with beam**

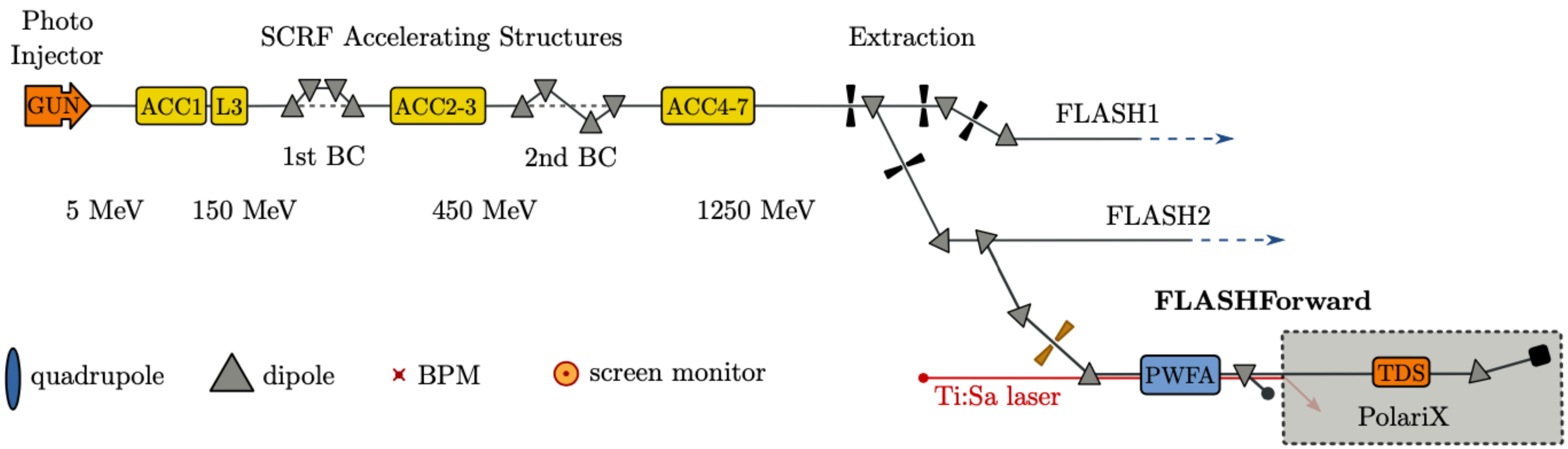
Bead-pull measurement at PSI



High power conditioning at CERN

Installation of the prototype at FLASHFORWARD▸▸

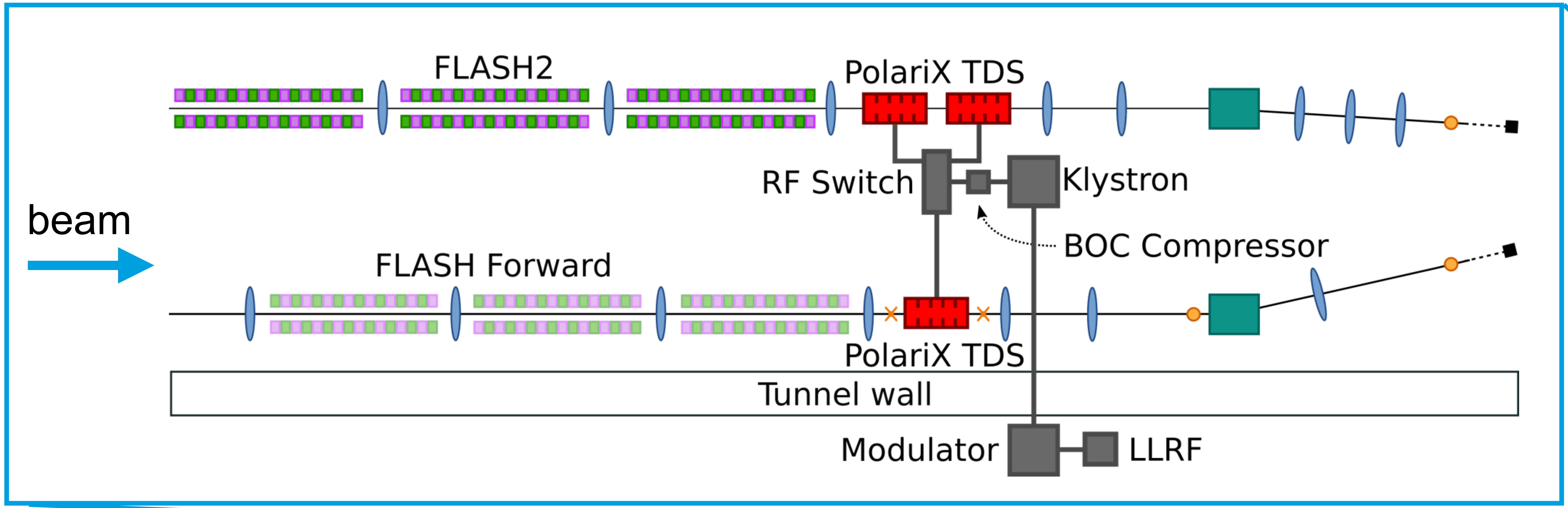
Design of the shared scheme between FLASHFORWARD▸▸ and FLASH2

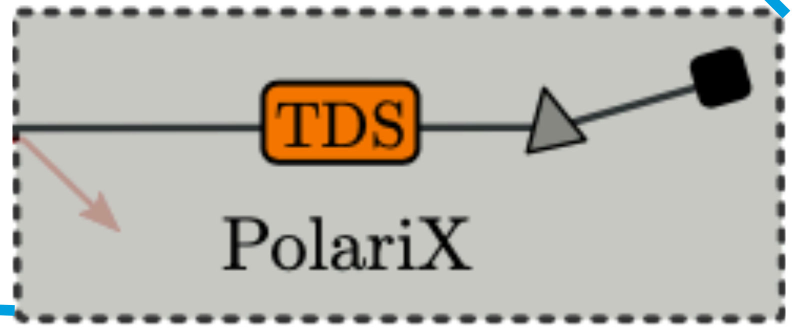


- **FLASHForward PolariX TDS beamline:** Richard D'Arcy
- **FLASH2 PolariX TDS beamline**: Mathias Vogt, Florian Christie
- **Technical coordinator:** Karsten Klose

Installation of the prototype at FLASHFORWARD▸▸

Design of the shared scheme between FLASHFORWARD▸▸ and FLASH2





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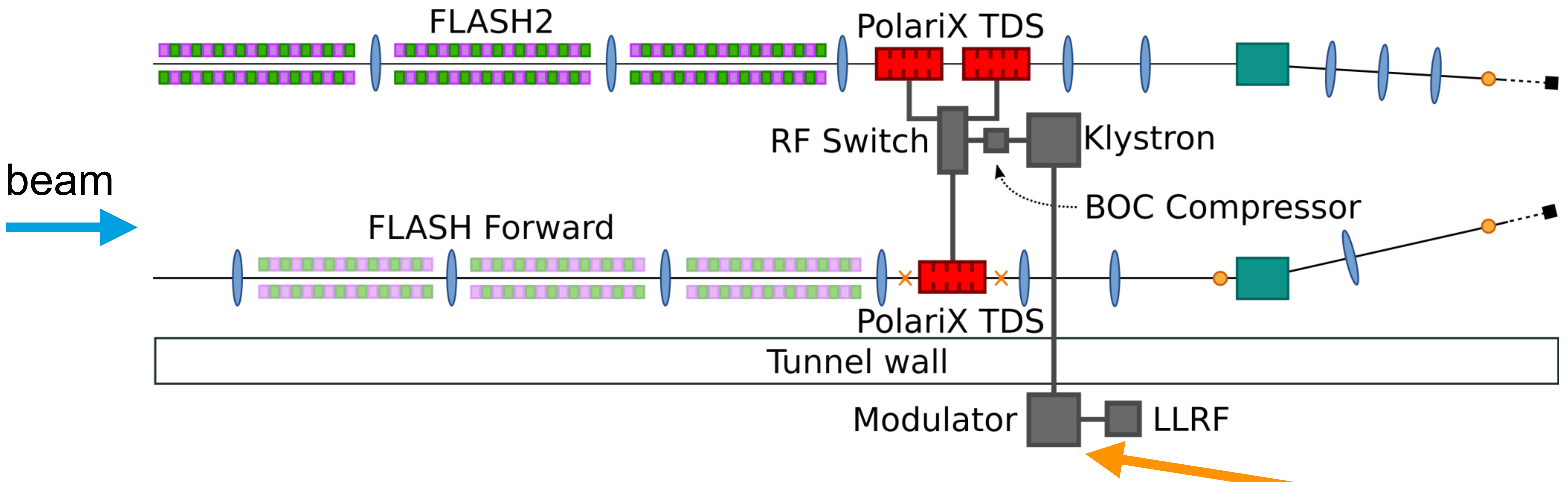
Installation of the prototype at FLASHForward

Modulator and amplifier supply pulses to the Klystron



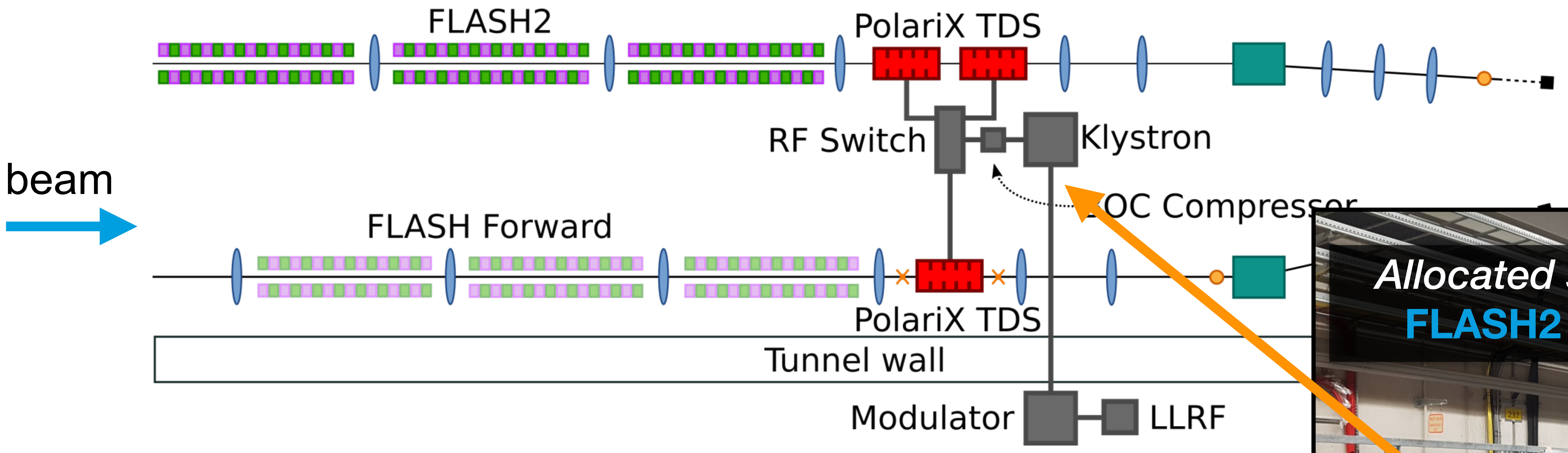
Ampegon Type M-Class Modulator

Located outside the tunnel to protect the electronics from radiation

Connected to the klystron via a ~12 m long high power cable

Installation of the prototype at FLASHFORWARD▸▸

Shared Klystron supplies power to one cavity at a time through a mechanical RF switch

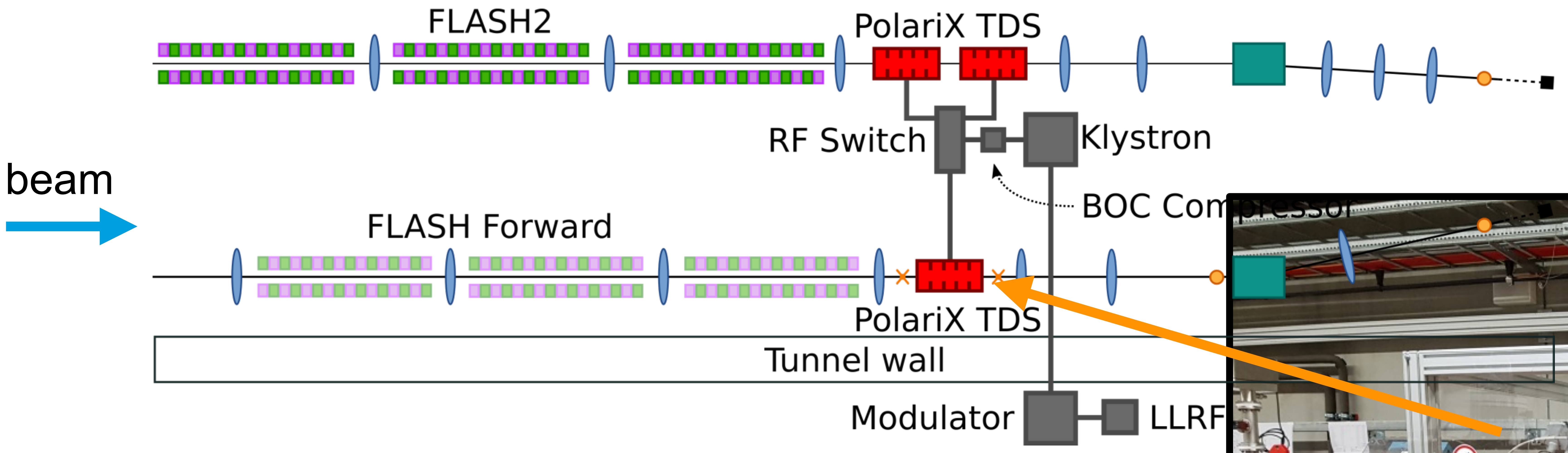


6MW Toshiba E37113A Klystron

Pulse compressor to be installed in 2021

Installation of the prototype at FLASHFORWARD▸▸

Prototype cavity installed in the FLASHFORWARD▸▸ beamline

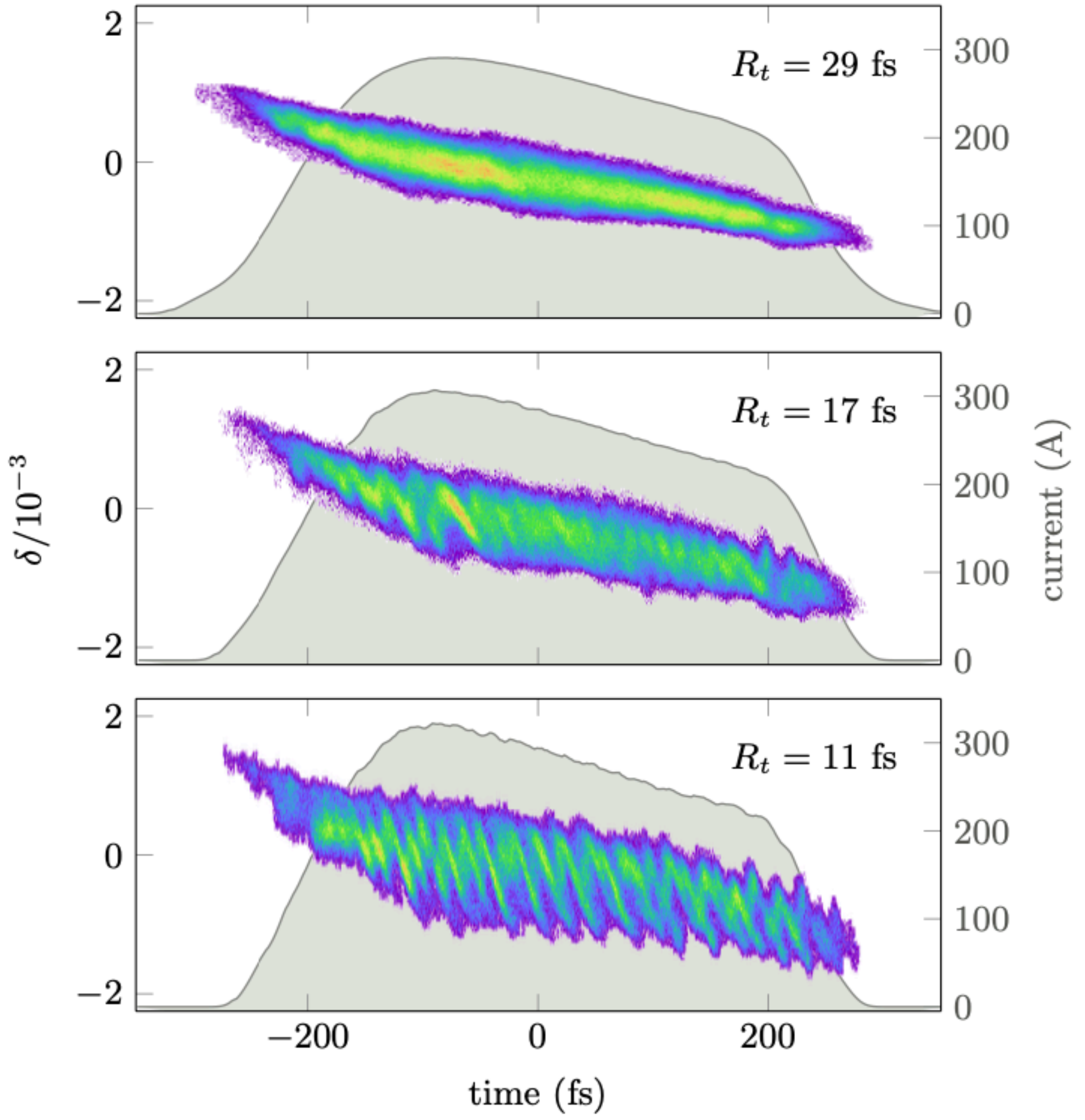


Prototype cavity installed in the FLASHFORWARD▸▸ beamline

First results with the FLASH electron beam

Longitudinal phase space reconstruction

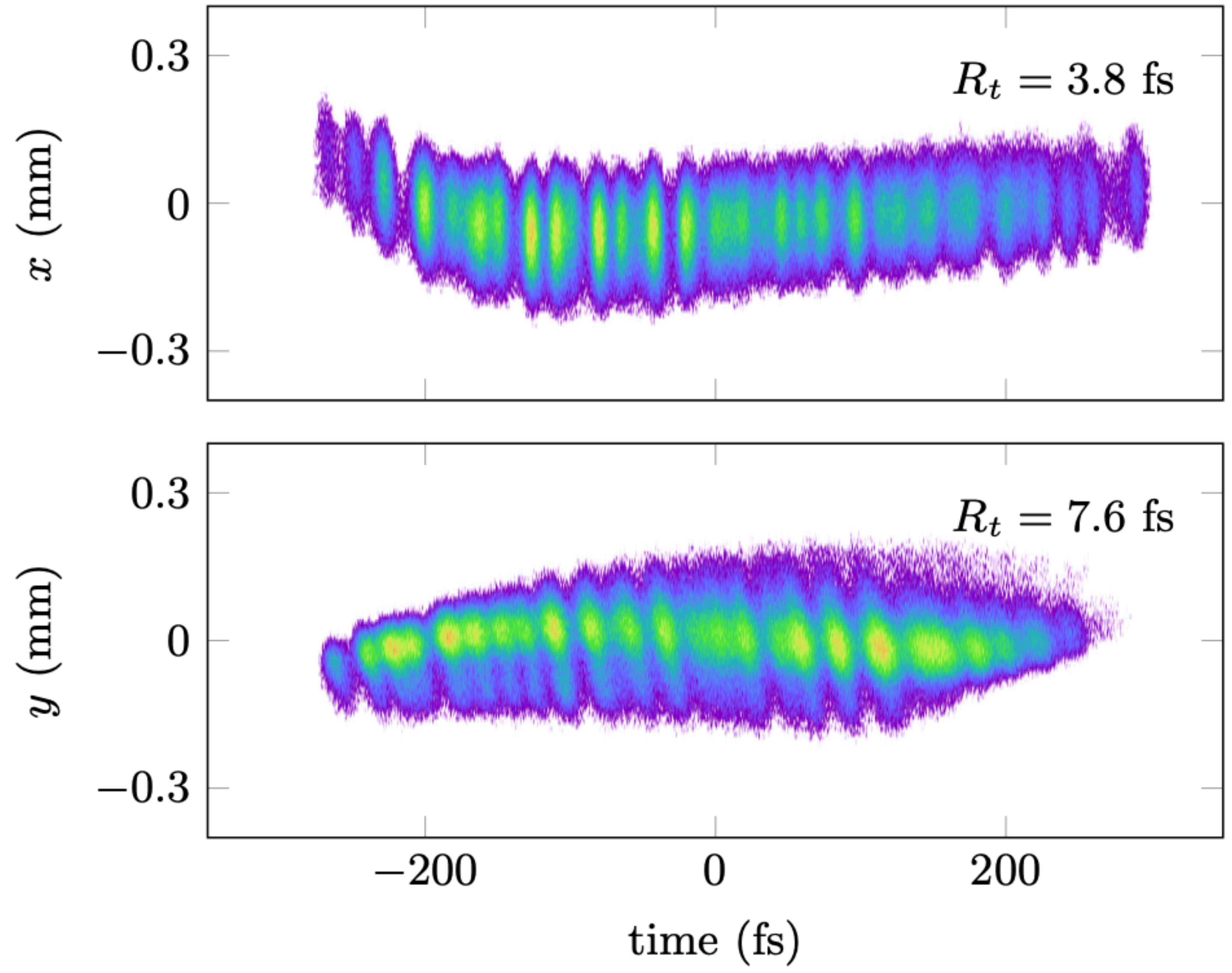
- Longitudinal phase space reconstruction ➞ the benchmark TDS measurement
- Increasing resolution begins to show interesting details in the beam e.g. micro bunching

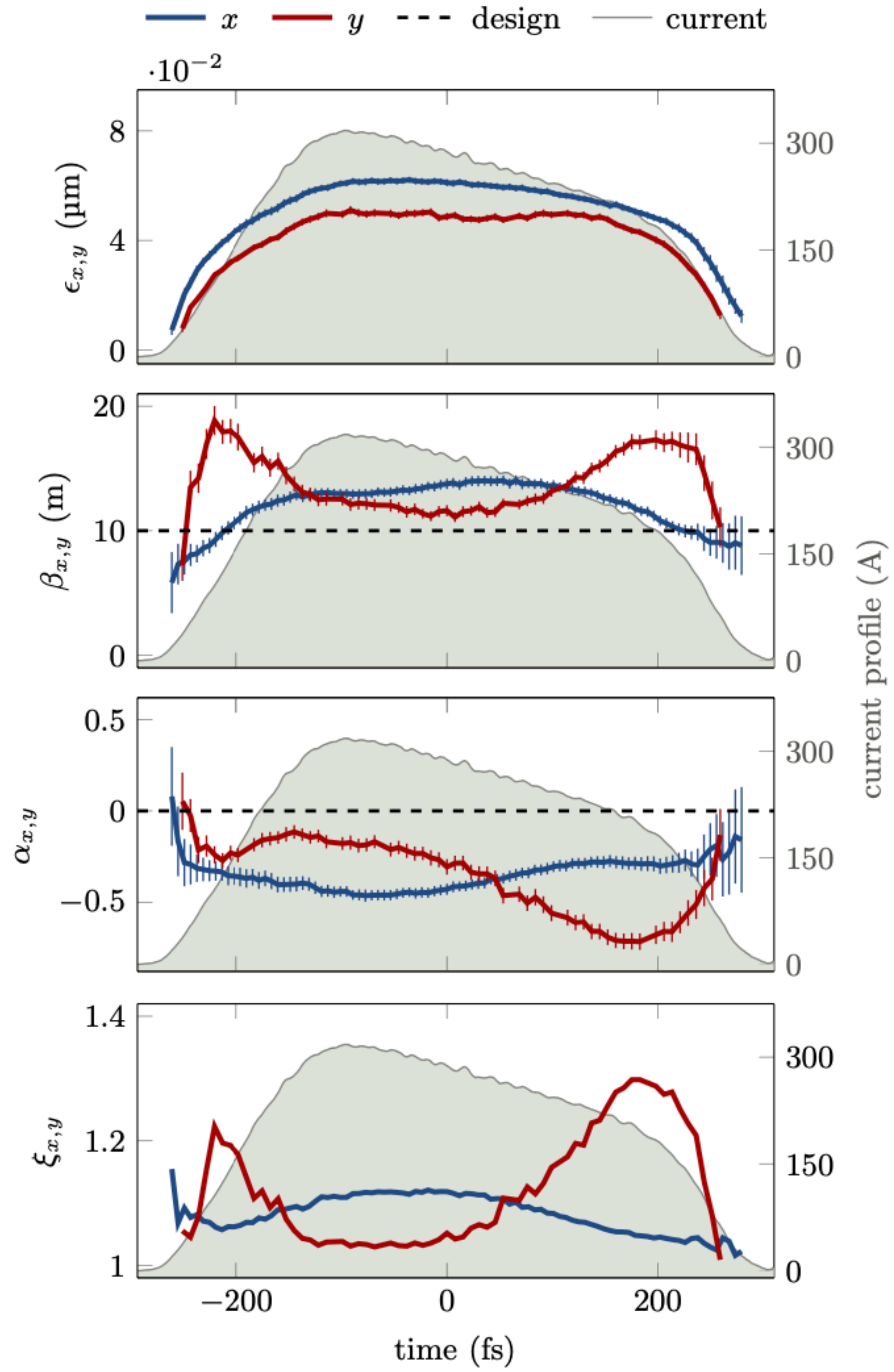


First results with the FLASH electron beam

Slice emittance measurements in both the *x-* and *y-*plane

- The phase rotator is moved to select both first the x- then the y-plane
- Centroid offsets are characterised in both planes
  - Enables online correction essential for e.g. plasma-based acceleration with large focussing fields
- Facilitates the diagnosis of slice properties in both transverse planes



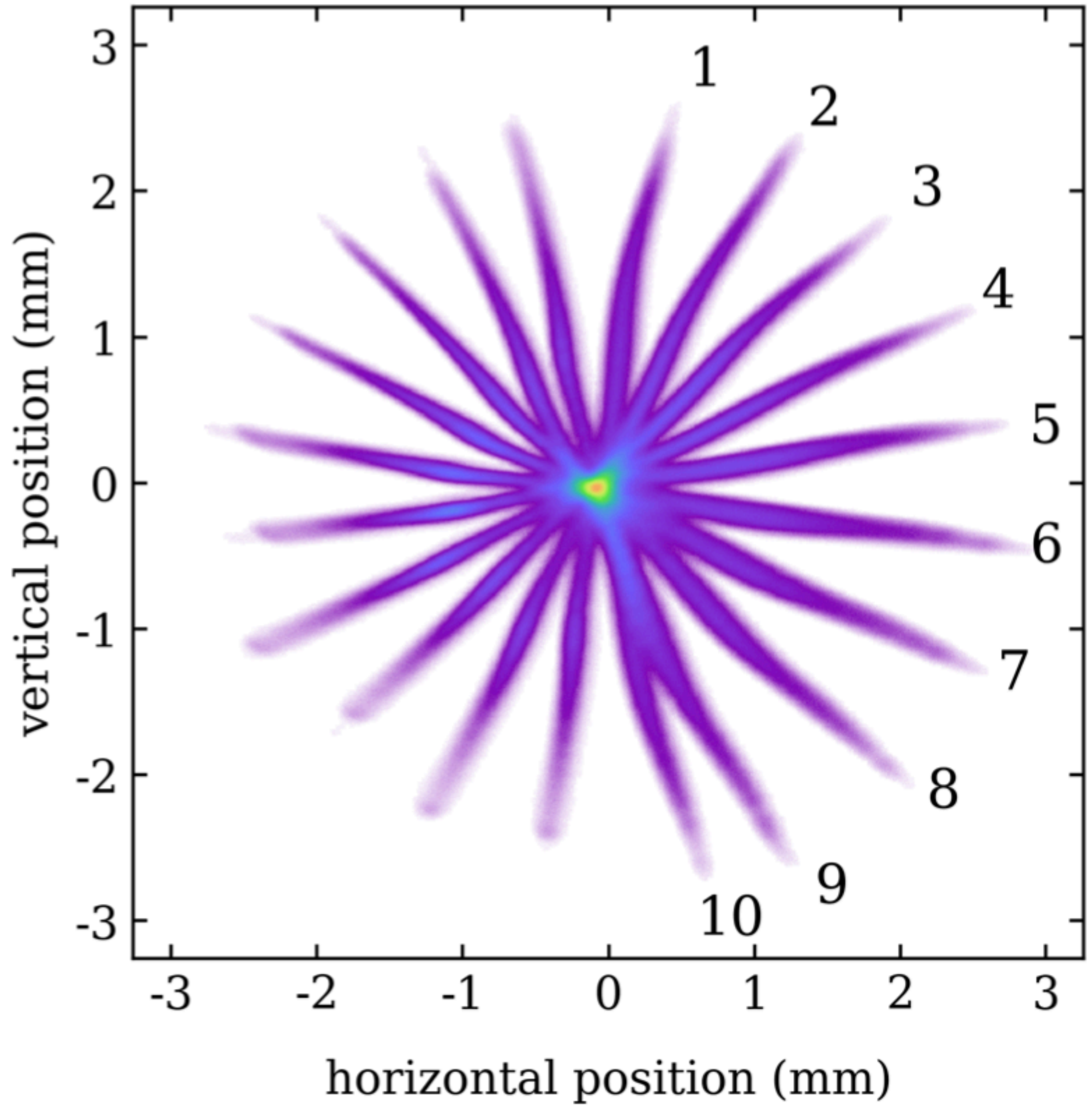


E = 1 GeV
Q = 1 nC
$\sigma_t \sim$ 250 fs rms

First results with the FLASH electron beam

Variable streaking of the beam with different phase shifter settings

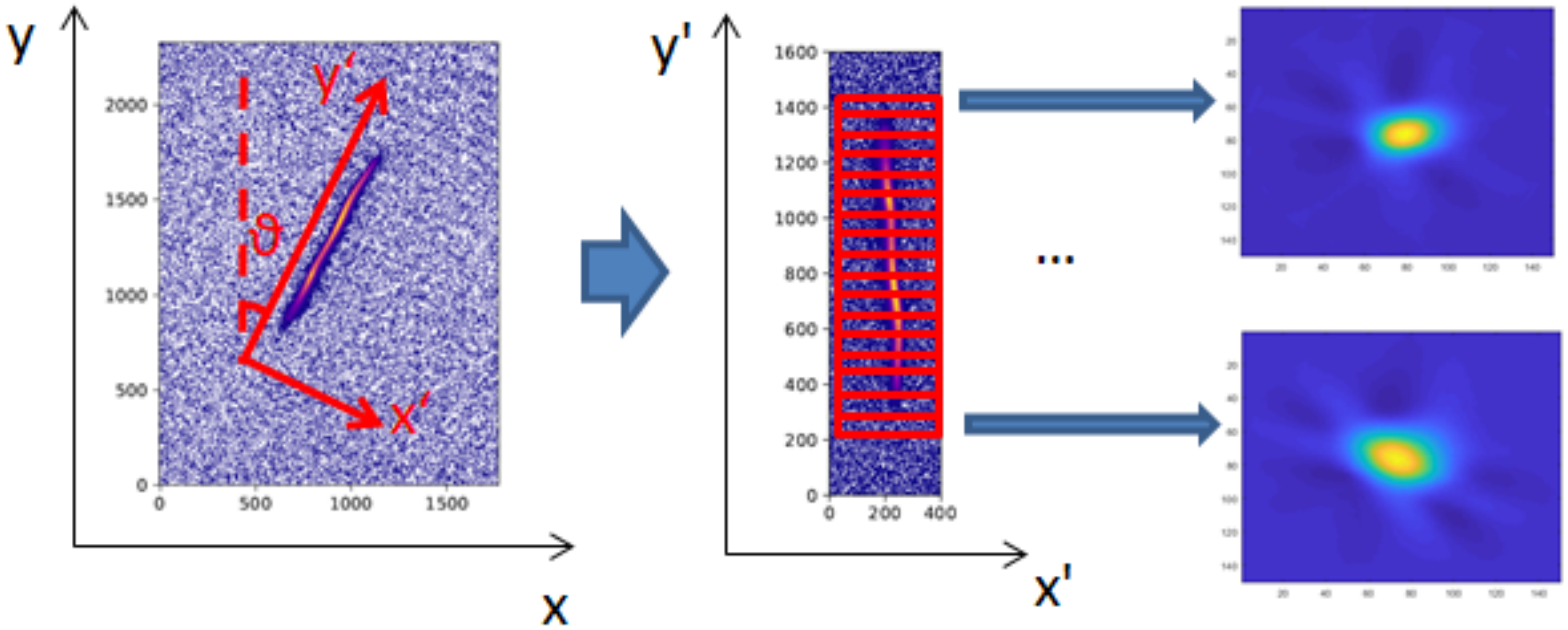
- The phase shifter is rotated from its zero position in motor steps
- Each image corresponds to a different position of the phase shifter
- Covers the entire 360 deg phase range of the x-y plane



E = 1 GeV
Q = 1 nC
σ_t ~ 250 fs rms

First results with the FLASH electron beam

Reconstruction of 3D charge-density distribution



- Images are collected at various streaking angles
- Slice properties are extracted from each polarisation
- 2D transverse profiles of each temporal slice are derived

First results with the FLASH electron beam

Reconstruction of 3D charge-density distribution

E = 680 MeV
Q = 300 pC
σ_t ~ 270 fs rms
R_t ~ 32 fs

- Images are collected at various streaking angles
- Slice properties are extracted from each polarisation
- 2D transverse profiles of each temporal slice are derived
- 3D charge-density beam distribution is tomographically reconstructed

Correlations between all planes in (x, y, z) space are quickly and easily visualised

Next hardware steps

FLASH2, SINBAD, and ATHOS will soon benefit from this unique device

- FLASH2:
  - Winter 2020: Installation of the first structure as well as the pulse compressor
  - Summer 2021: Installation of the second structure
- SINBAD:
  - Winter 2020: Delivery of both structures
  - Spring 2021: Installation of both structures
- ATHOS
  - Spring 2021: Delivery and installation of both structures

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Many more exciting results on the way…!

POLARIX — Polarisable X-band Transverse Deflection Structure

Summary and outlook

- POLARIX prototype has been developed, implemented, and successfully commissioned by an international collaboration
- First commissioning results are very promising → the prototype will next be used in the coming months for optimisation and characterisation of the plasma-acceleration process at FLASHFORWARD▸▸
- More cavities are on the way to various experimental facilities at DESY and PSI → many more exciting results to follow soon…!