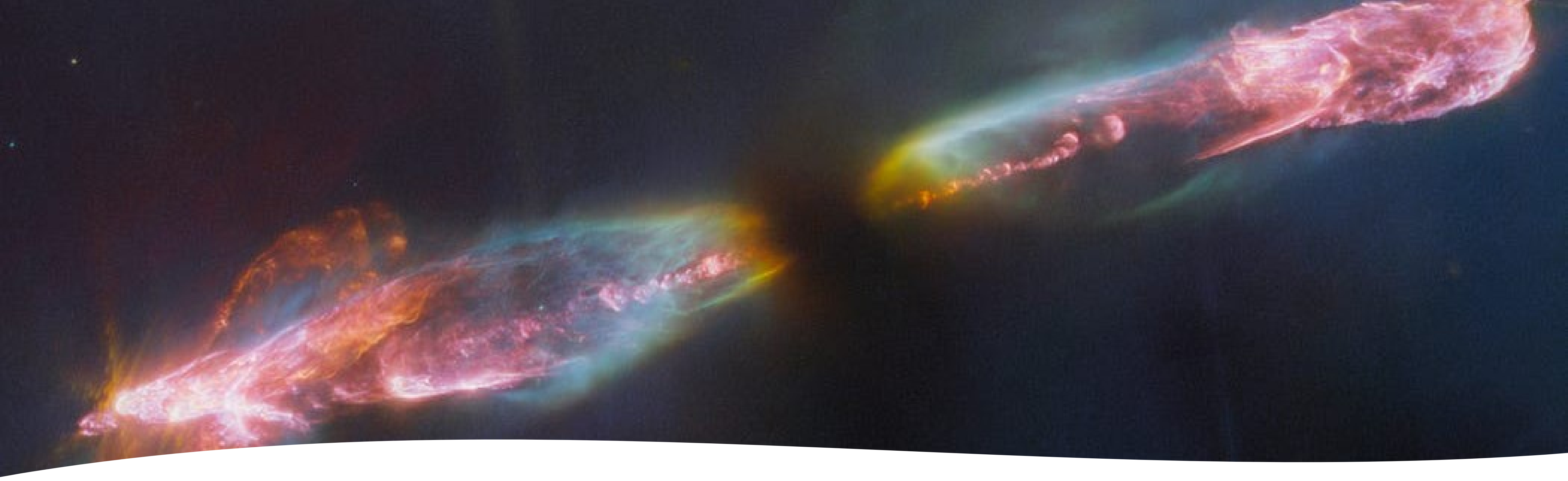


Superradiant THz radiation generation (STERN)

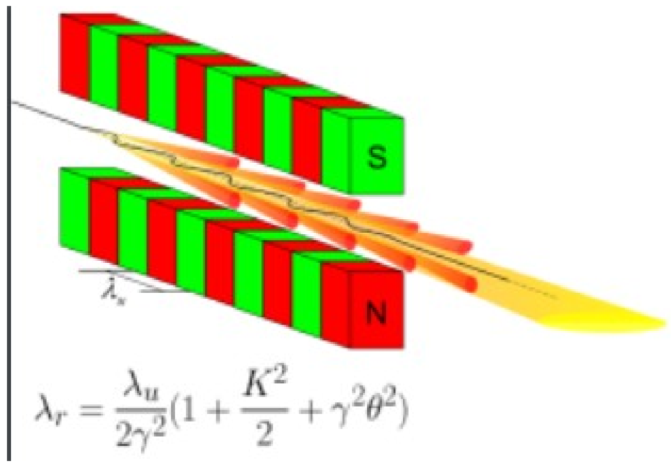
Francois Lemery, Karel Peetermans, Winni Decking, Klaus Floettmann, Nina Golubeva, Nils Lockmann, Bernd Steffen, Marie Kristin Czwalinna, Martin Dohlus, Igor Zagorodnov, Jonah Richards, Torsten Wohlenberg, Lukas Mueller, Daniel Thoden, Lucy Mueller, Riko Wichmann, Stuart Walker, Marc Guetg, Shan Liu, Sergey Tomin, Weilun Qin, Tianyun Long, Serge Bielawski, Mikhail Krasilnikov, Gianluca Geloni, Dirk Lipka, Artem Novokshonov, Gero Kube, Ingmar Hartl, Evgeny Negodin, Matthias Scholz

Ultrafast beams and Applications 2024, CANDLE, Yerevan, Armenia

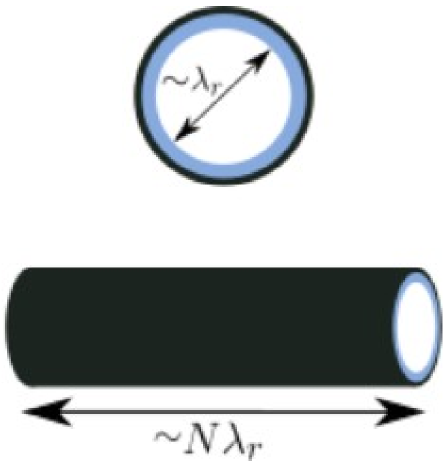
User demands

- From Zalden et al. Terahertz Science at European XFEL, European XFEL Report XFEL. EU TN-2018-001-01.0 (2018); users would like:
  - Tunable bandwidth between 1 (single-cycle) and 0.05 (20 cycles)
  - Frequency range between 0.1 (3) to 30 THz
  - Pulse fluence/field strength: More than 2 MV/cm which corresponds to 10 GW/cm^2
    - Assuming e.g. a 1 ps pulse duration, this would correspond to fluences of 10 mJ/cm^2
    - Some examples for a spot size ~ wavelength are:
      - 3 mJ at 100 GHz
      - 30 uJ at 1 THz
      - 300 nJ at 10 THz
      - Note these numbers vary depending on the bandwidth of request THz
  - CEP stable
  - Repetition rate should operate at minimum 100 kHz, but ideally at 4.5 MHz (burst).
  - Synchronization better than 0.1/frequency
    - 1 ps at 100 GHz
    - 20 fs at 5 THz
    - 3.3 fs at 30 THz

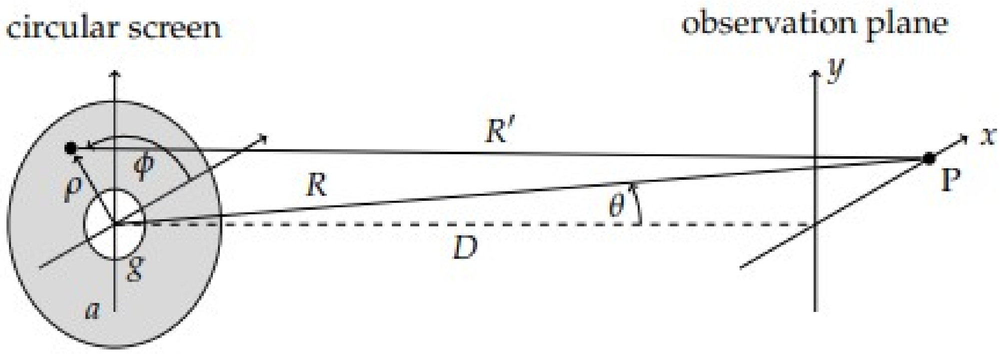
Electron beam based radiation sources



Undulator



Cherenkov (wakefields)



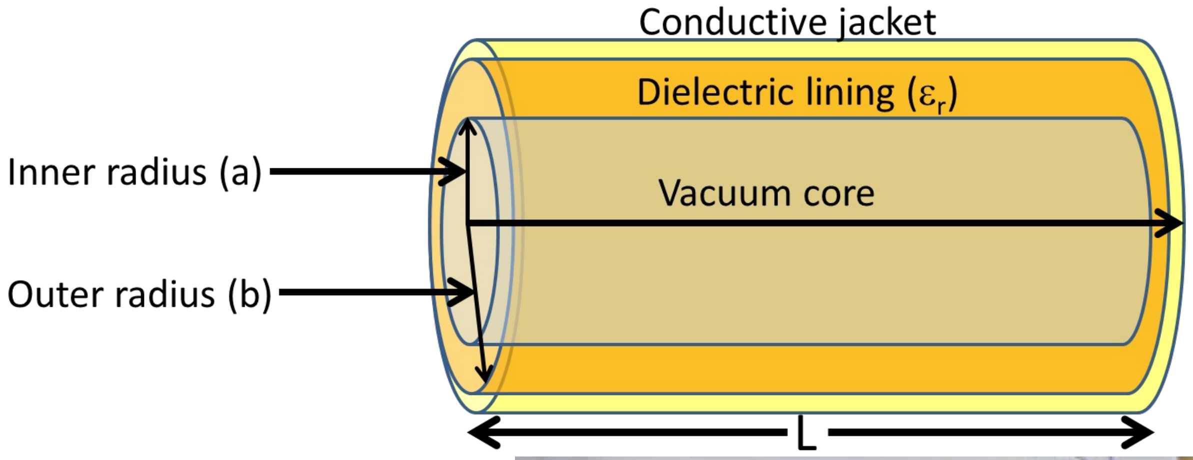
Diffraction

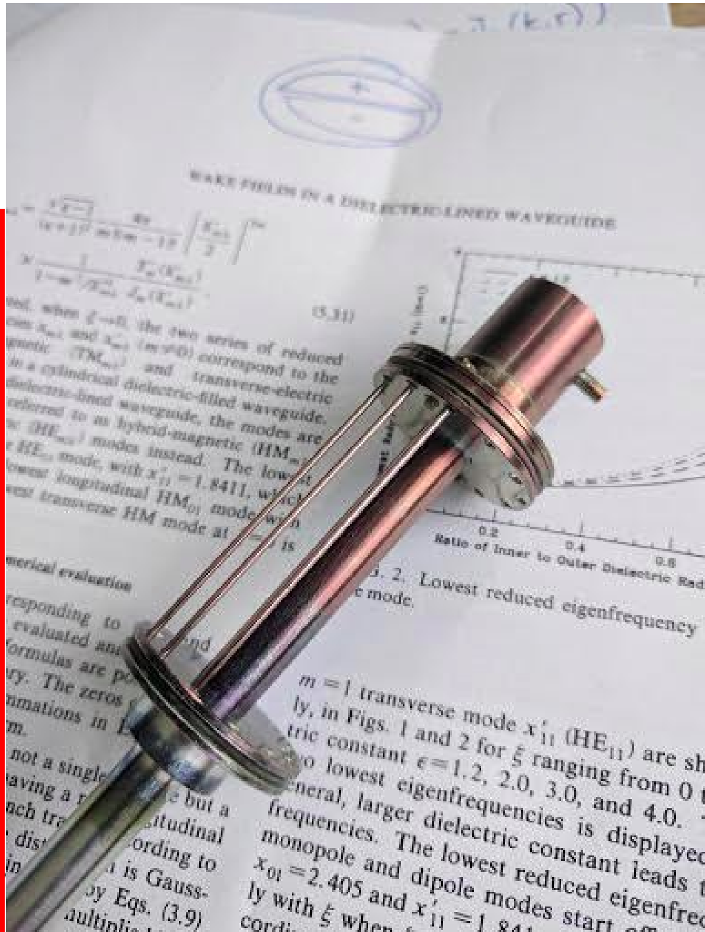
- At 16 GeV, undulator approaches are challenging to cover the THz regime (m for 18 GeV)
- Cherenkov approaches are energy independent and depend on inner aperture and thickness
- Diffraction radiation is also appealing for its ability to produce very broadband radiation on the order of uJ.

Cherenkov waveguides

Dielectric-lined waveguides

- Dielectric-lined waveguides (DLW), corrugated metallic structures support wakefield deceleration e.g. “structure wakefield acceleration” (SWFA).
- Wakefields have group velocity (unlike plasma) and can be extracted for various applications.
- Stability of radiation depends essentially on qF term.
  - Here, q is charge, F is the form factor, L is the structure length, and is the inner radius.
  - See K. Floettmann, et. al *Rad.* (2021) **28**, 18-27 for details.





TM01
Field Eqns.

$$k_1 = \omega\sqrt{\frac{1}{c^2} - \frac{1}{v_p^2}}$$

$$k_2 = \omega\sqrt{\frac{\epsilon_r}{c^2} - \frac{1}{v_p^2}}$$

$$k_z = \frac{\omega}{v_p}.$$

$$E_z = \begin{cases} B_1 J_0(k_1 r) e^{i(\omega t - k_z z)} & 0 \le r < a \\ B_2 F_{00}(k_1 r) e^{i(\omega t - k_z z)} & a \le r \le b \end{cases}$$

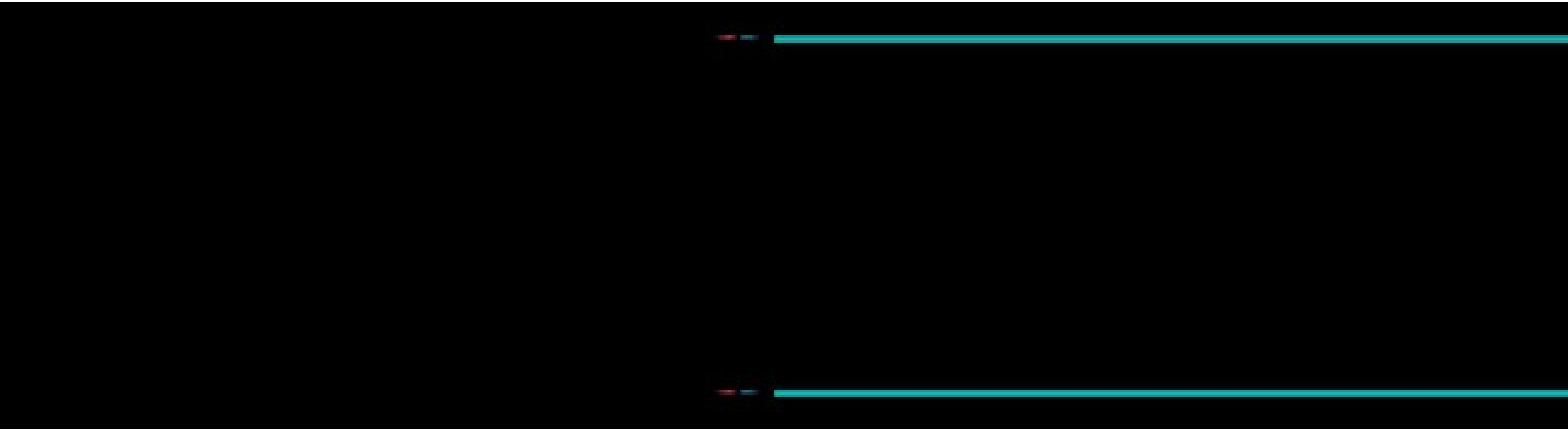
$$E_r = \begin{cases} \frac{-ik_z}{k_1} B_1 J_0'(k_1 r) e^{i(\omega t - k_z z)} & 0 \le r < a \\ \frac{-ik_z}{k_2} B_2 F_{00}'(k_2 r) e^{i(\omega t - k_z z)} & a \le r \le b \end{cases}$$

$$H_\phi = \begin{cases} \frac{-i\omega\epsilon_0}{k_1} B_1 J_0'(k_1 r) e^{i(\omega t - k_z z)} & 0 \le r < a \\ \frac{-i\omega\epsilon_r\epsilon_0}{k_2} B_2 F_{00}'(k_2 r) e^{i(\omega t - k_z z)} & a \le r \le b \end{cases}$$

Energy $E^{\mathrm{rad}} = q^2F^2|K_\parallel|L = q^2F^2L\frac{Z_0c}{2\pi r_1^2}.$

Power $P = q^2F^2\frac{Z_0k_0^2c}{16\pi}$

Dielectric Tube



Diffraction radiation – an extremely broadband source

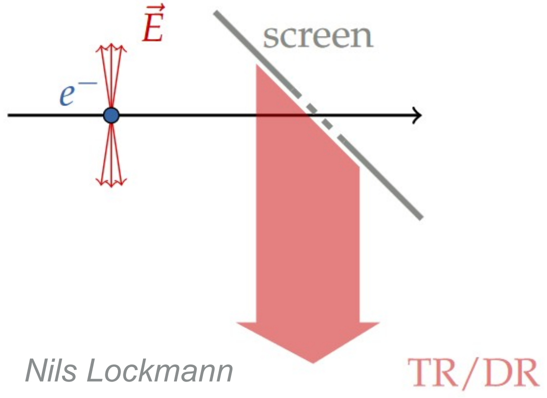
- An electron beam passing through an aperture leads to diffraction radiation.
- In the limit the aperture goes to zero and the foil size goes to infinity, the energy/spectrum is given by:

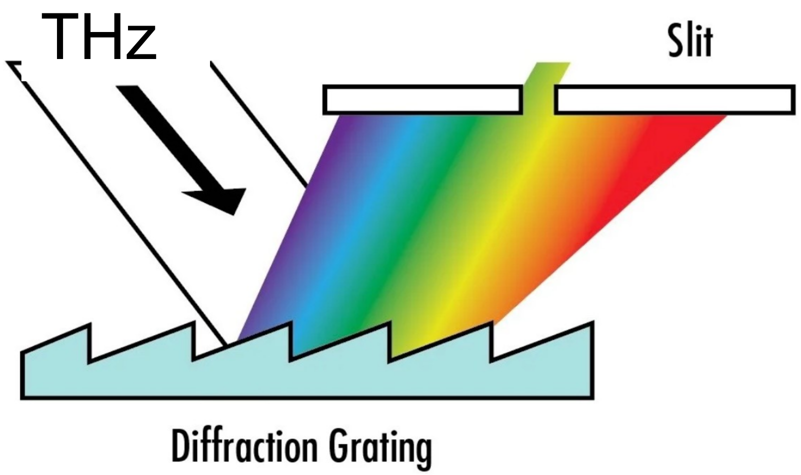
$$\frac{dU}{d\omega} = \frac{q^2 F^2}{2\pi^2 \epsilon_0 c}(ln(\gamma) + ln(2) - 0.5)$$

- Used in CRISP to reconstruct beam current profile using THz radiation, see disseration of N. Lockmann

→ Could be used at STERN as a THz source for users

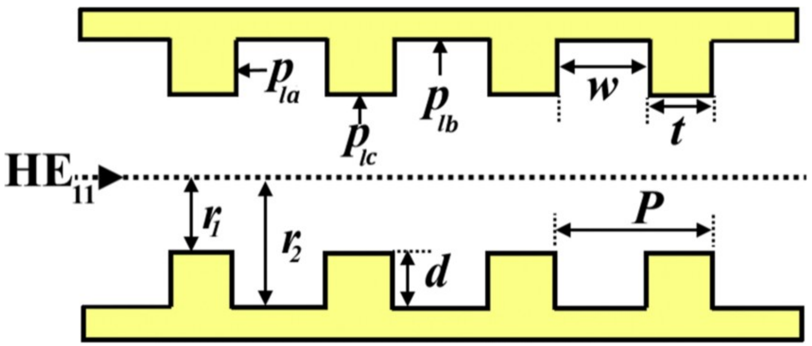
- Select frequency and bandwidth using grating filtering system

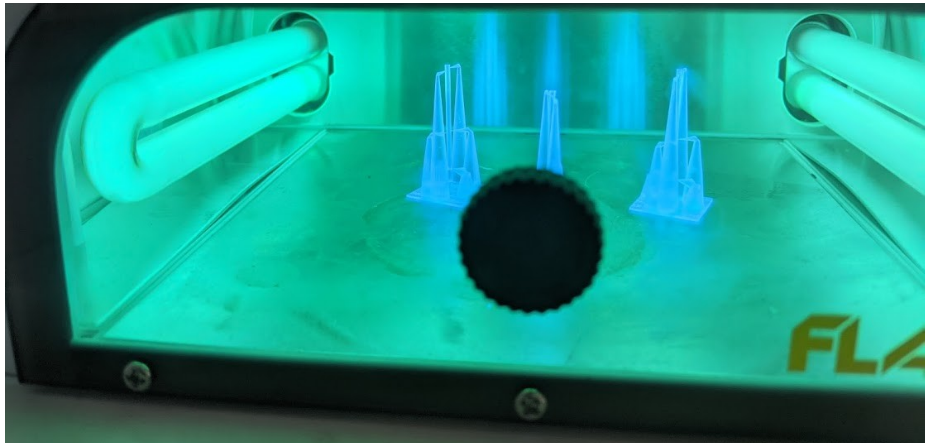




THz structures and development

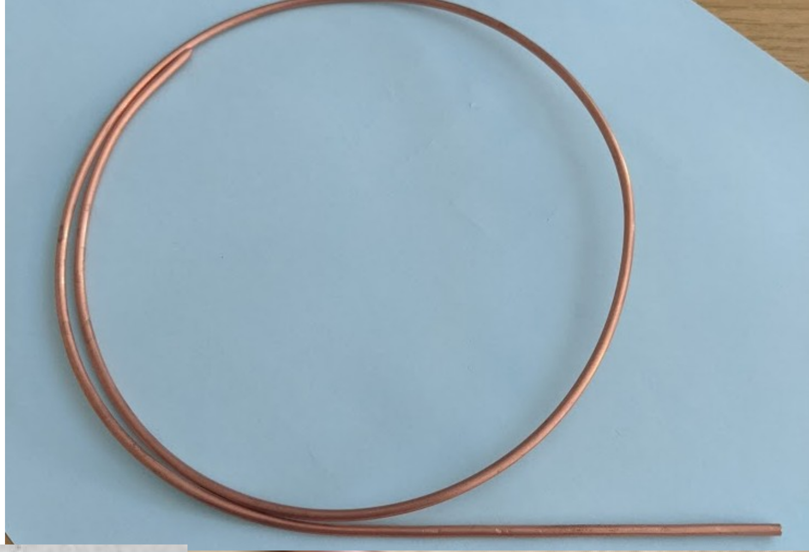
- Currently investigating several types of waveguides: dielectric lined, corrugated, and bi-metallic (Armenian colleagues).
- Corrugated structures are more challenging to produce in cylindrical symmetries, while dielectric and bimetallic waveguides can be produced more easily
  - Dielectric e.g. fused silica can be drawn and coated, limited to thicker capillaries due to fragility.
  - Dielectrics can also be deposited with gas or oxidation
  - Metallic surfaces can also be deposited.
- Photonic crystal fibers are also attractive, however at high frequencies material losses are significant in fused silica.

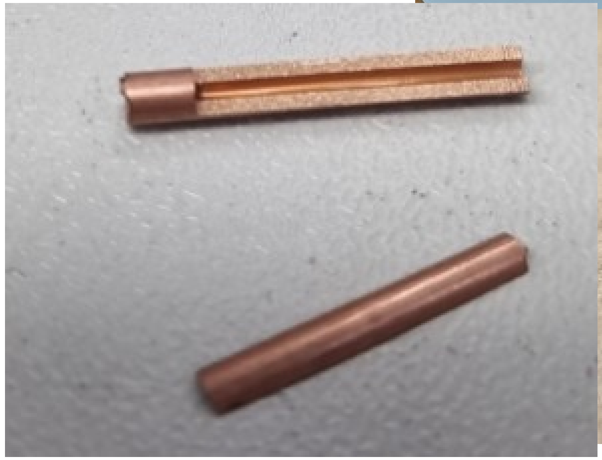


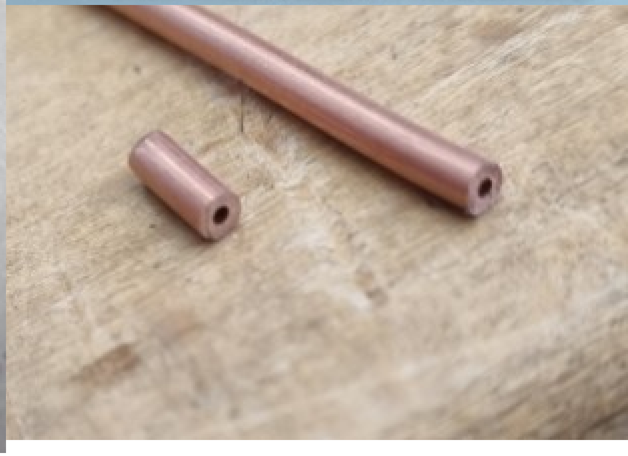


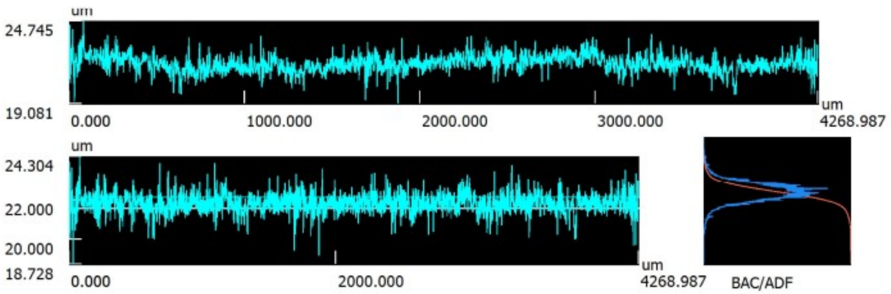
Drawn copper capillaries

- Clemens (MEA) has made great progress on cutting these structures
  - Flat/straight cuts
  - Longitudinal/Open cuts
  - Vlasov cuts
- Collaboration with R. Zierold (CHyN) to investigate coating with Atomic Layer Deposition ALD.
  - Very thin layers, as required for high frequencies, can be realized with a precision on an atomic layer thickness with various materials.
- In discussion with XFEL colleagues to develop method of characterizing these waveguides
- Another possibility is to use fs-scale bunches at REGAE and observe wakefield effect.

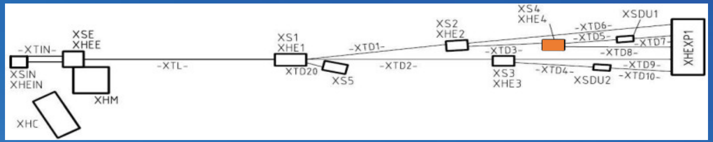




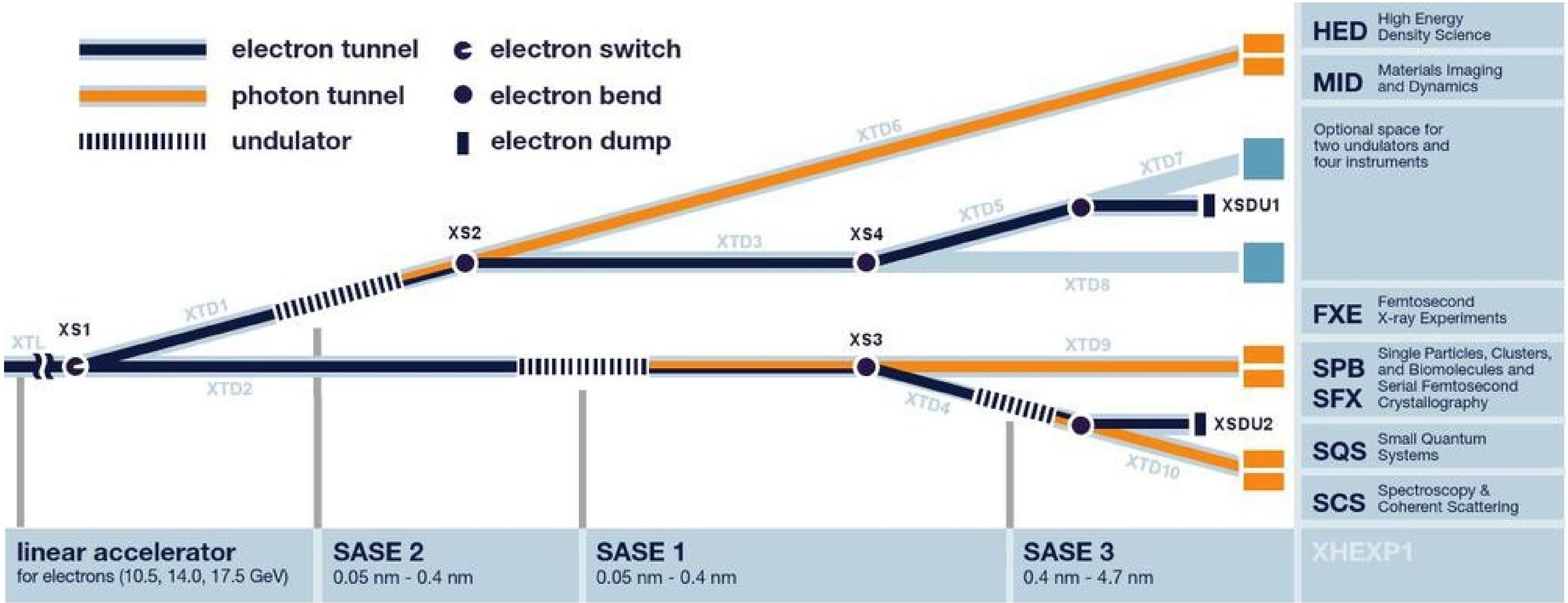




surface roughness (ZMQS)



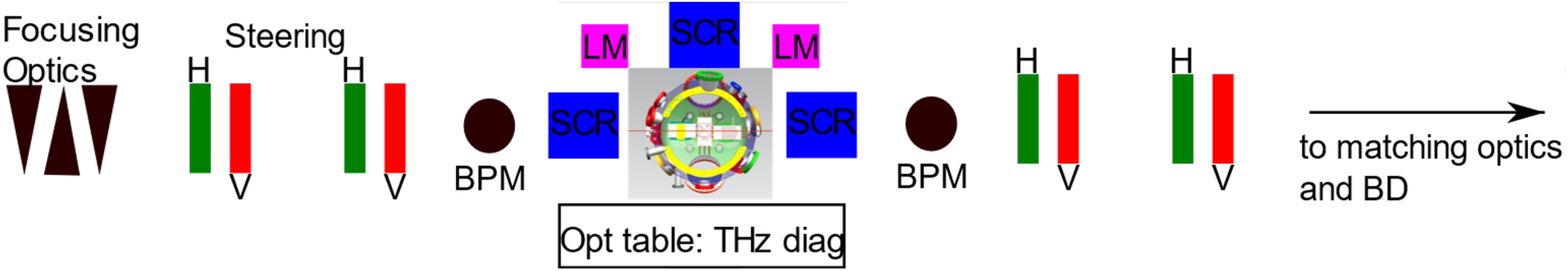
Experimental area overview



- Location approximately z=2950 (XS4)
- XTD8 will be diagnostics area and will be accessible during operation.
- Interested in symmetric beta function of beta_x=beta_y ~ 1 m .
- Need also to ensure proper conditions for BD+

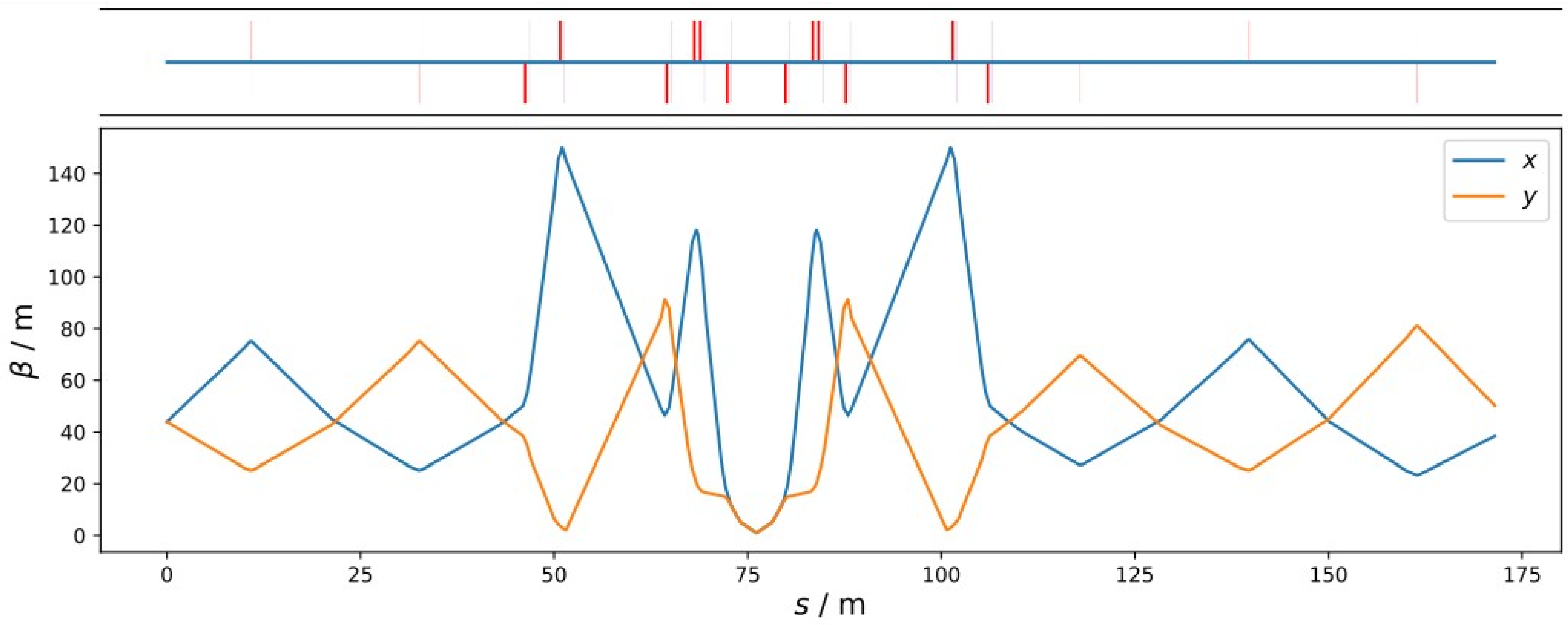
General layout of experimental area (2025)

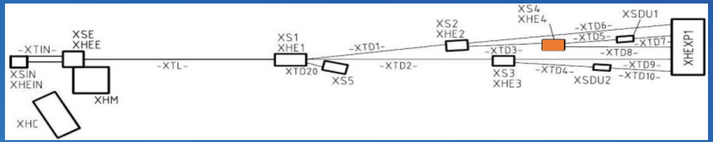
- Quadrupoles for focusing
- Dipoles for orbit bump to separate e & X beams
- BPMs for positioning
- Loss monitors (LM)
- Beam size diagnostics (screens + wire scanner)
  - Screen positions determined by resolutions to measure waist



Lattice design

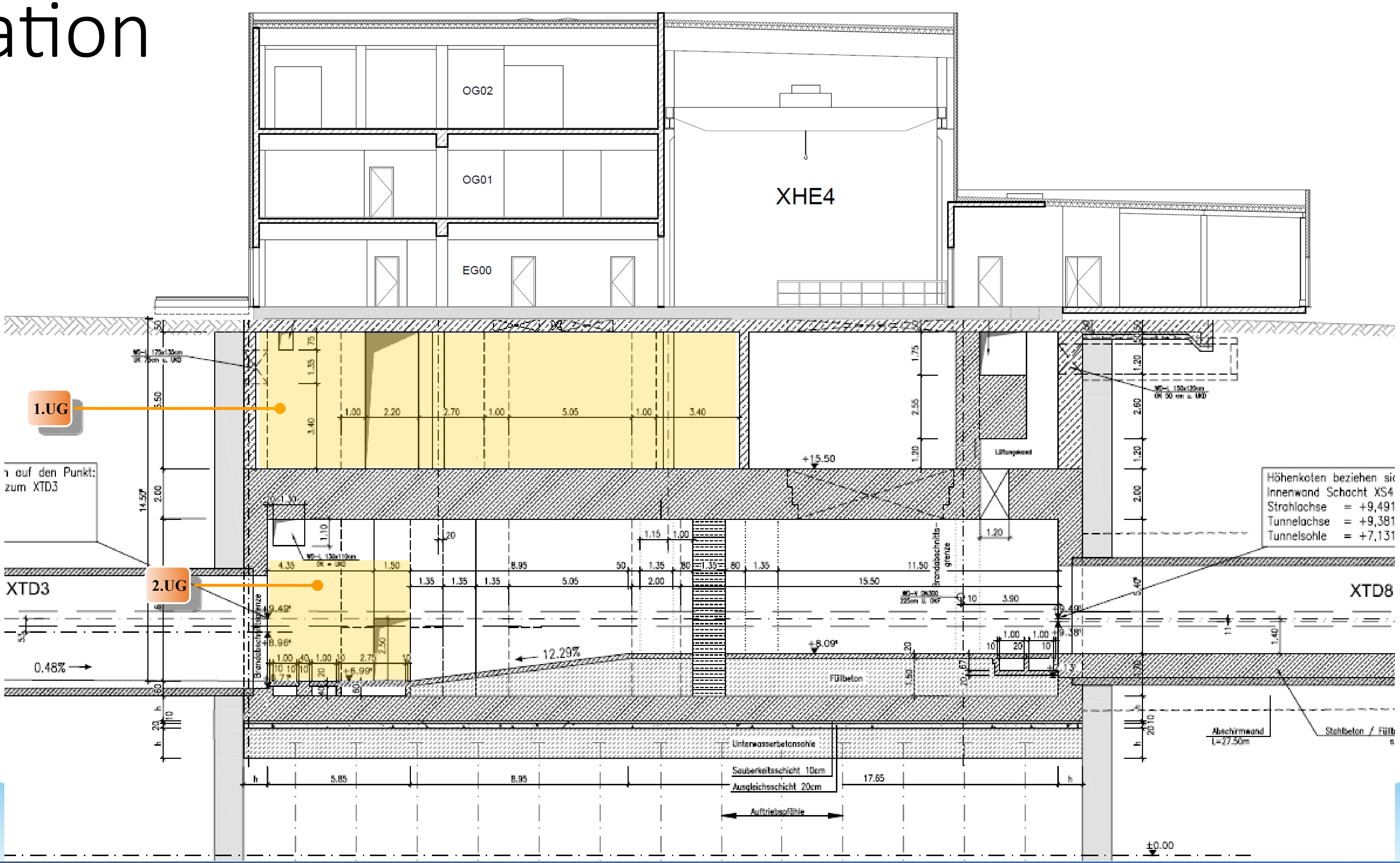
- Mini-beta design to produce 1 m beta functions while maintaining requirements for beam dump.
- Design includes 10 new quadrupoles
- At 16 GeV, , .





XS4 / XHE4 Overview

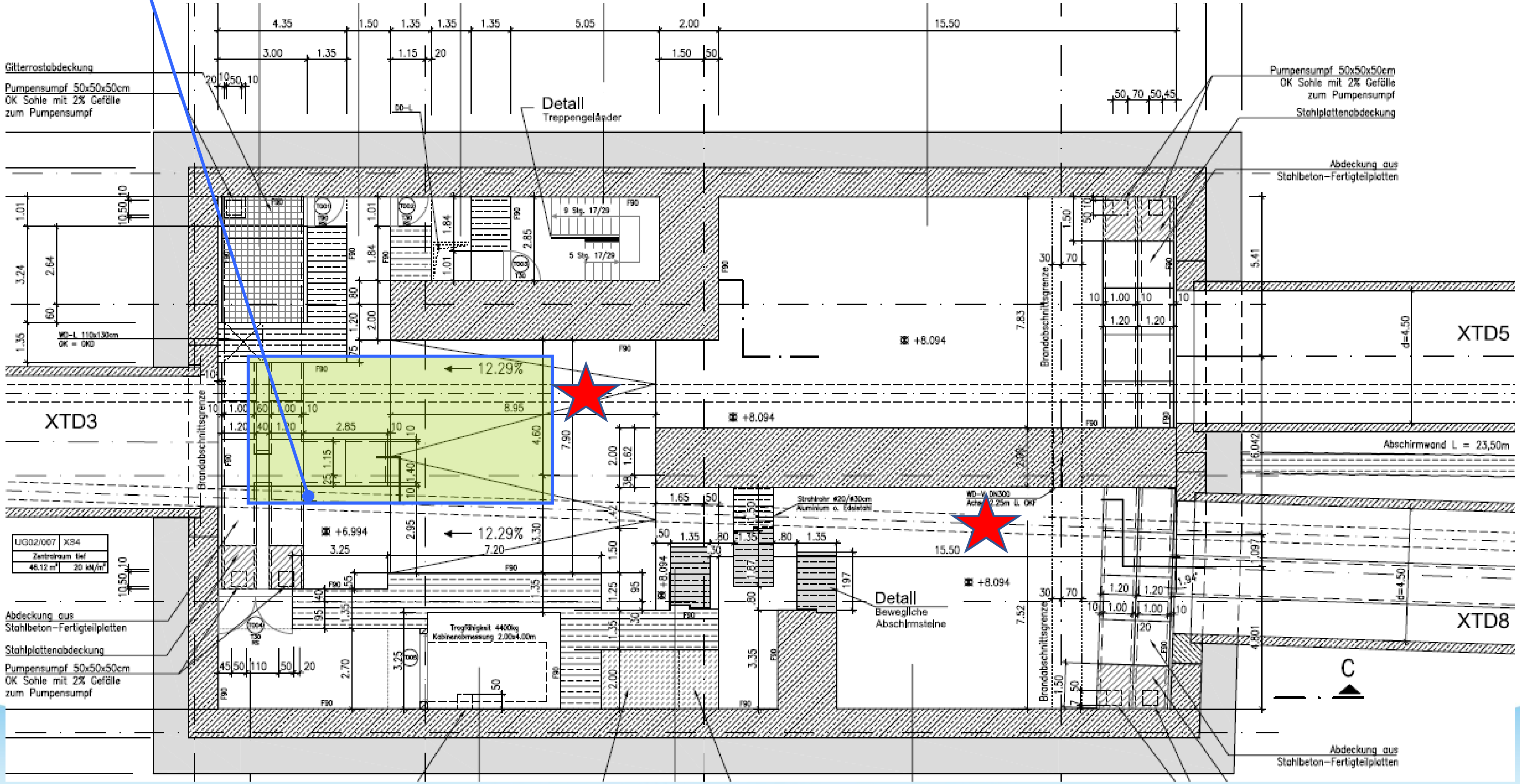
Location



UG02/007	XS4
Zentralraum tief	
46.12 m²	20 kN/m²

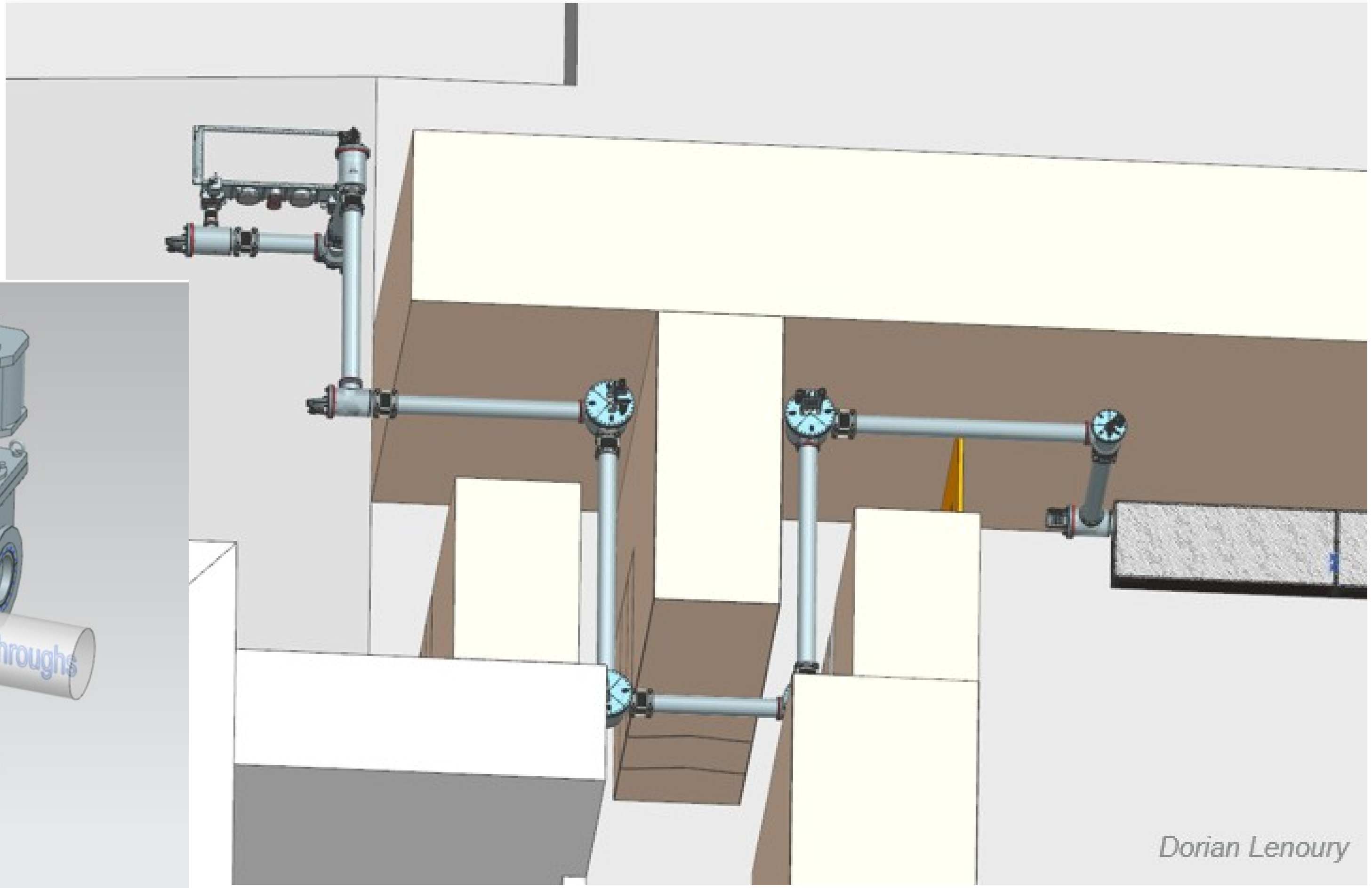
2 Electronic racks

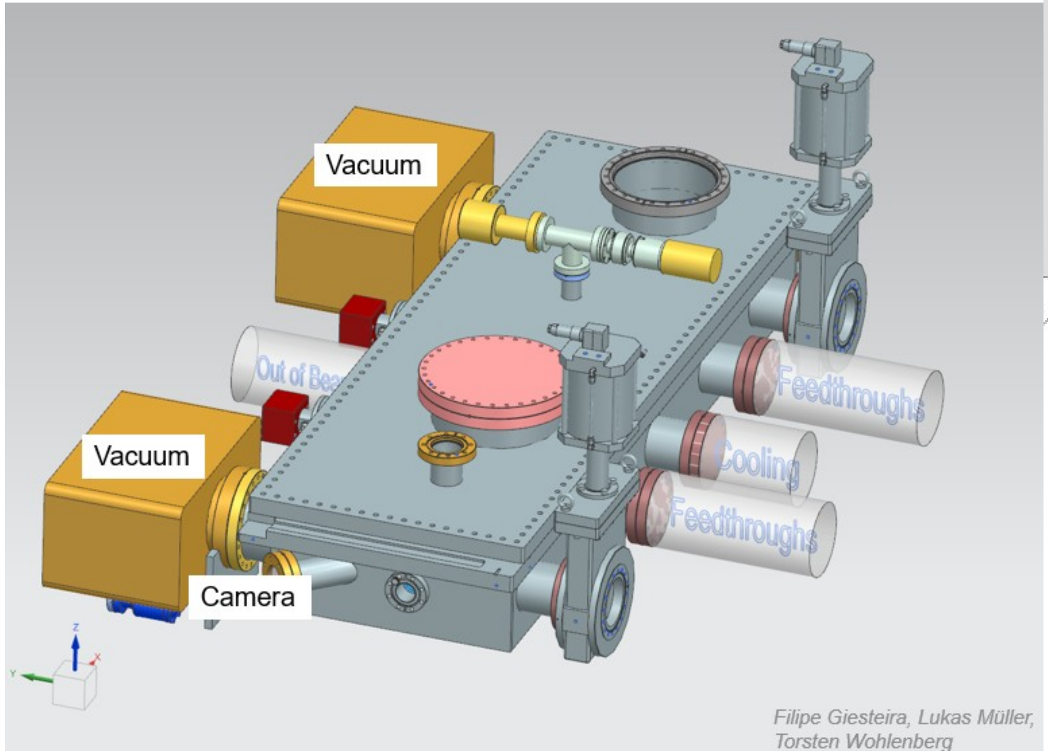
WP17 Standard diagnostics
Responsible: M. Steckel, K Wittenburg



General layout of experimental area (2025)

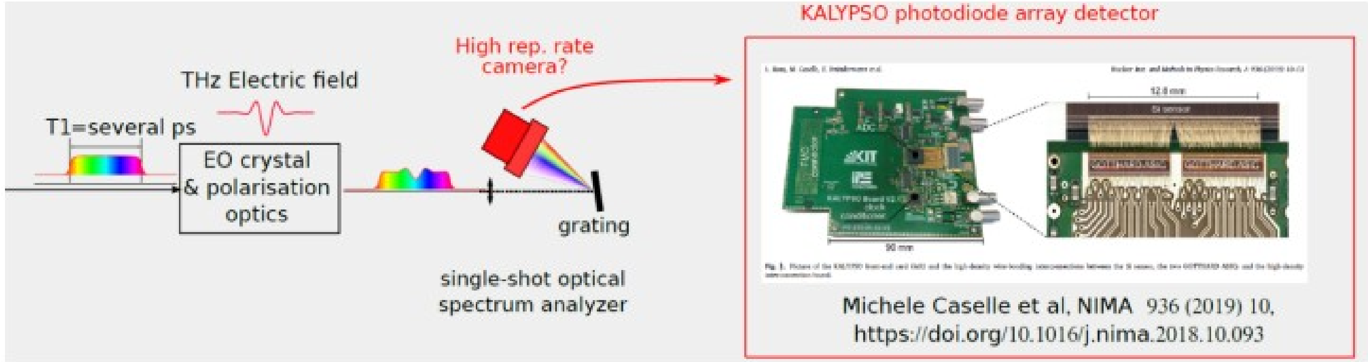
- THz transport shown from chamber to user accessible diagnostics area after concrete chicane.
- Chamber design complete out for production
- Beam transport design underway, initial design shown (right), details by Karel



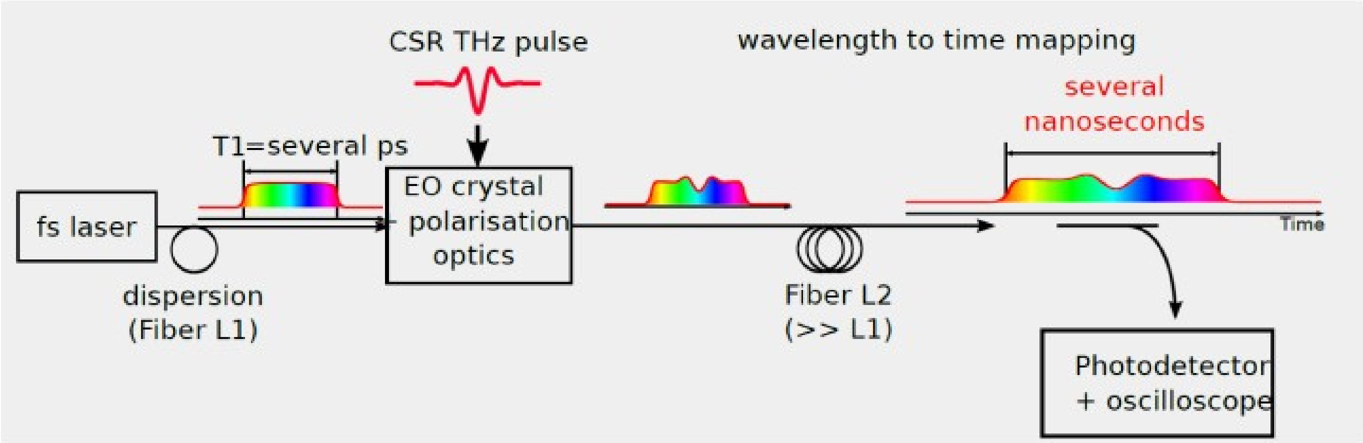


THz diagnostics – collaboration with Lille. Courtesy Serge Bialawski

In this talk: Single-shot Electro-Optic detection using chirped pulses



Spectral decoding option



Photonic time-stretch option

Notes:

- EO strategy (using a 1030 nm laser) guided by the DESY/KIT/PSI design – most recent (?) design [B. Steffen et al., RSI 91, 045123 (2020)]
- Time-stretch -> can be seen as as a way to make a spectrometer when L2 is large (known as Dispersive Fourier Transform -- DFT)

THz diagnostics – spectrum approach

- Can also use spectral-based approach using gratings and detector arrays (CRISP), picture right from thesis of Nils Lockmann (now MSK).
- Technique uses

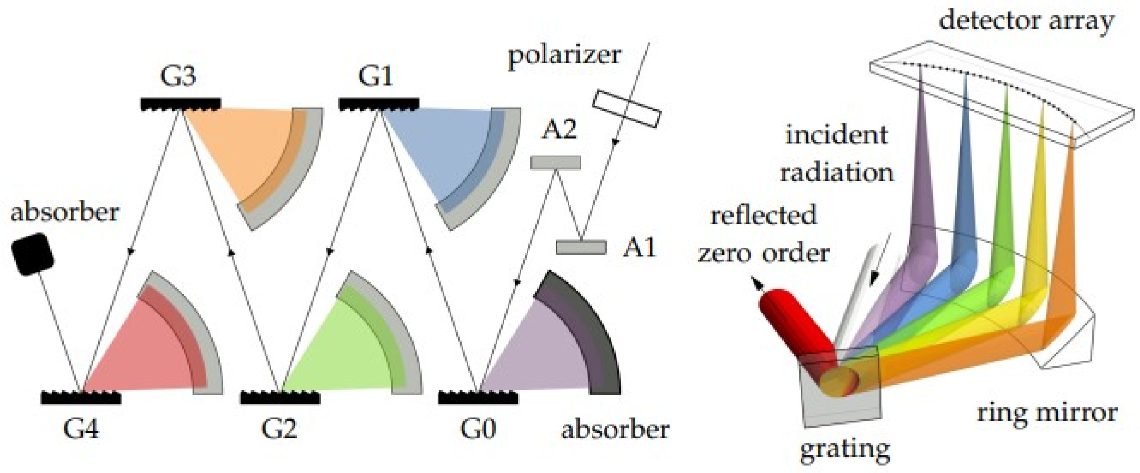
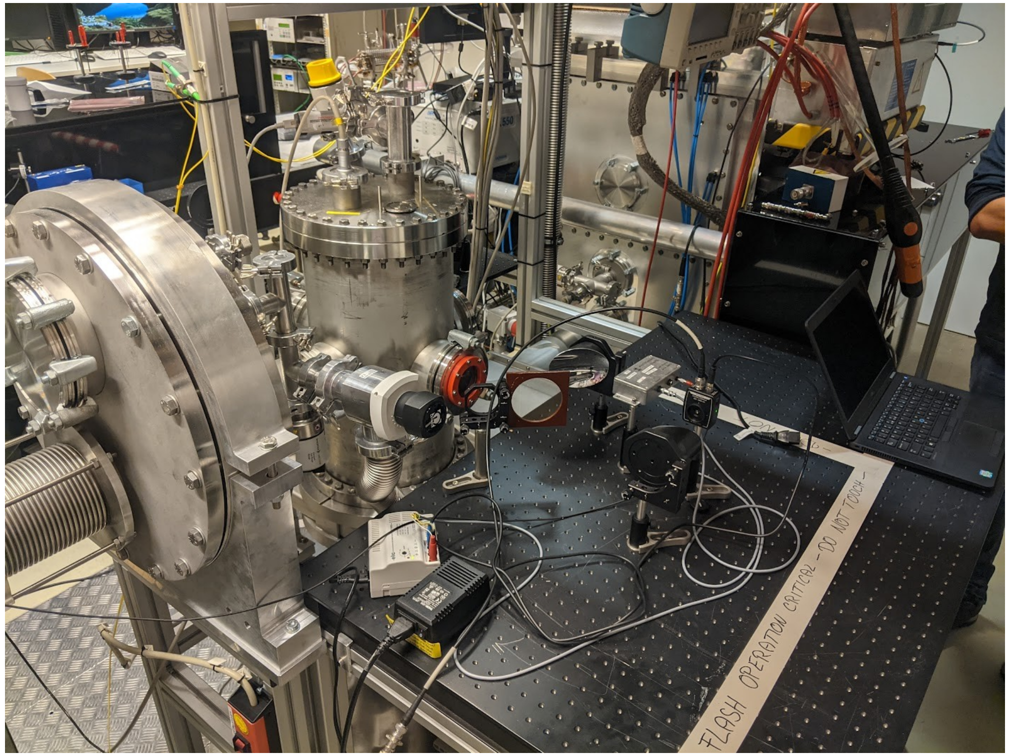


FIGURE 4.12: Layout of the CRISP spectrometer with five cascaded gratings (left). The polarizer transmits only the horizontal polarization for which the spectrometer is designed. The mirrors A1 and A2 are used to align the radiation inside the spectrometer. The first grating filters out high frequencies that would otherwise lead to higher order dispersion effects. For gratings G1-G4, a parabolic ring mirror focuses the radiation on a pyroelectric detector array above (right). Adapted from [Wes12].

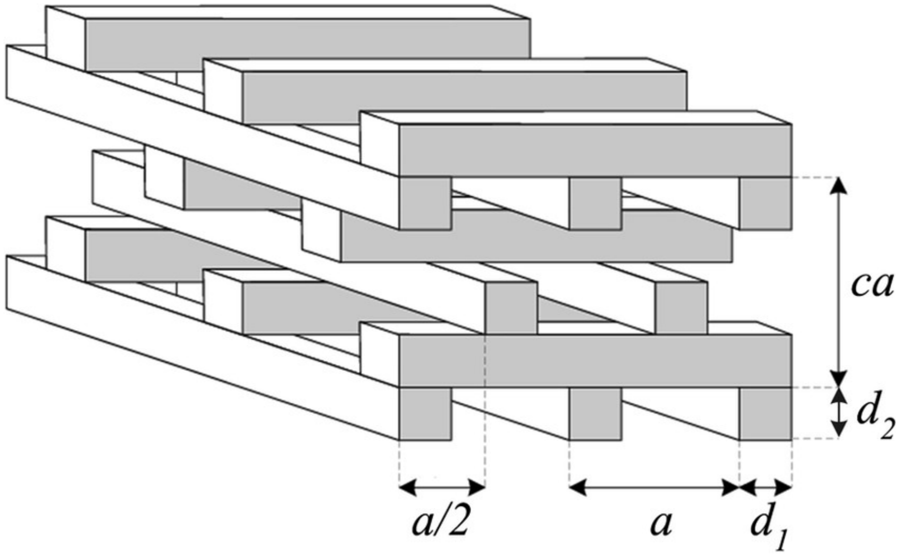


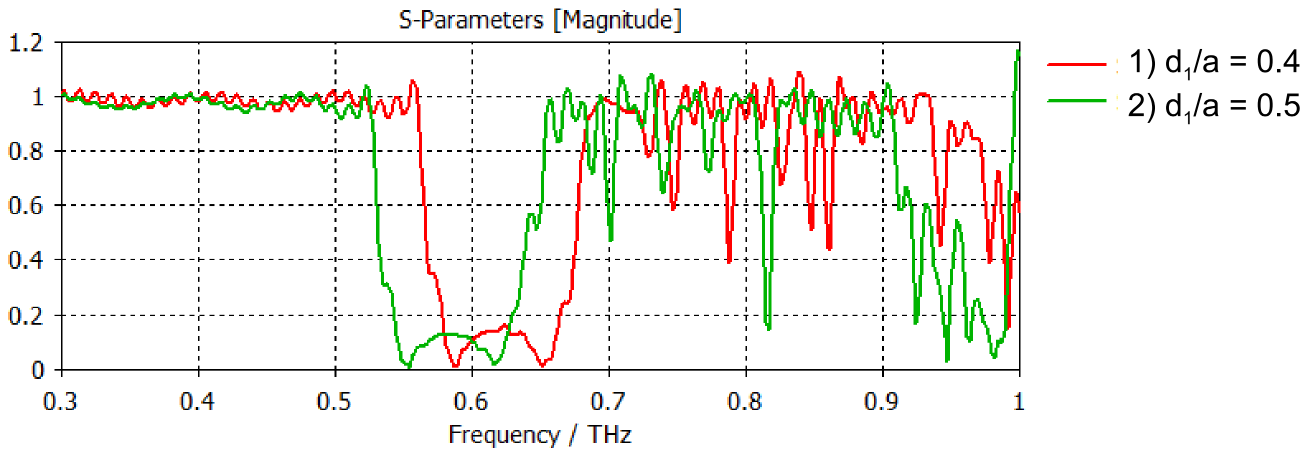
- Looking to conduct measurements at FLASH where there is a source of up to 30 THz.
- Need to characterize waveguides, dispersion difficult but losses are more achievable.

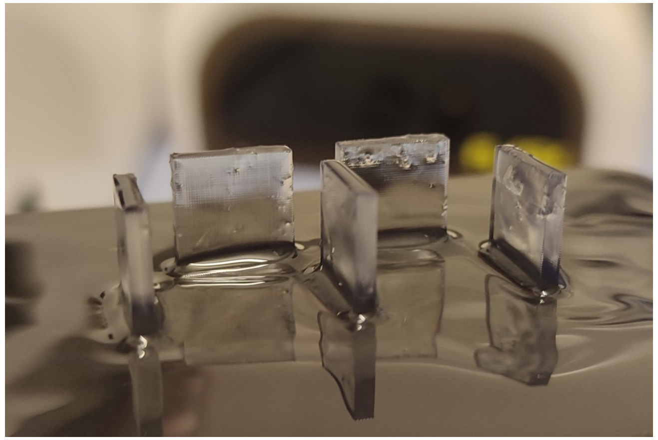
Design and Fabrication of THz-Bandpassfilters

Using 3D-printed Photonic Crystals

- Woodpile Structure for a complete photonic band gap
- Parameters:
  1) a = 200 µm, d_1= 80 µm and d_2= 70,7 µm (d_1/a = 0.4)
  2) a = 200 µm, d_1= 100 µm and d_2= 70,7 µm (d_1/a = 0.5)
- Simulation with CST show bandgap of ΔBG = 0.11 at 0.53 – 0.64 THz and 0.57 – 0.68 THz
- 3D printing with STL-3D-printer by Asiga



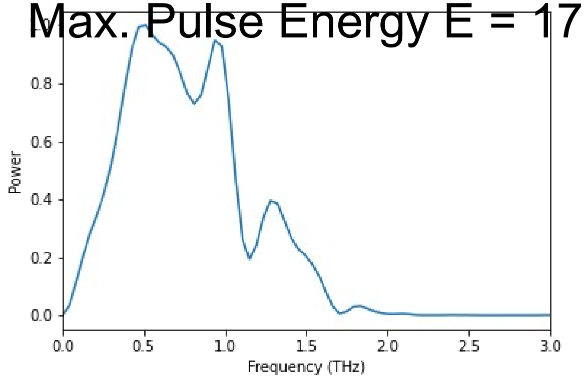


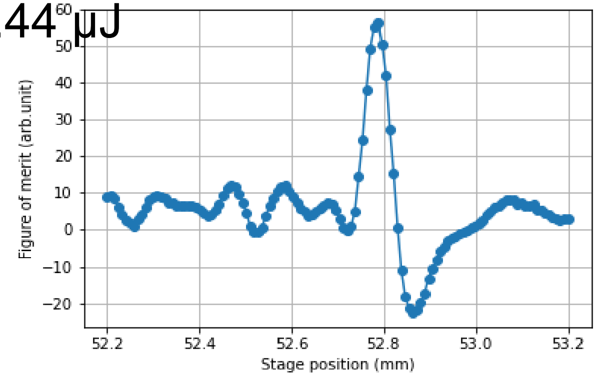


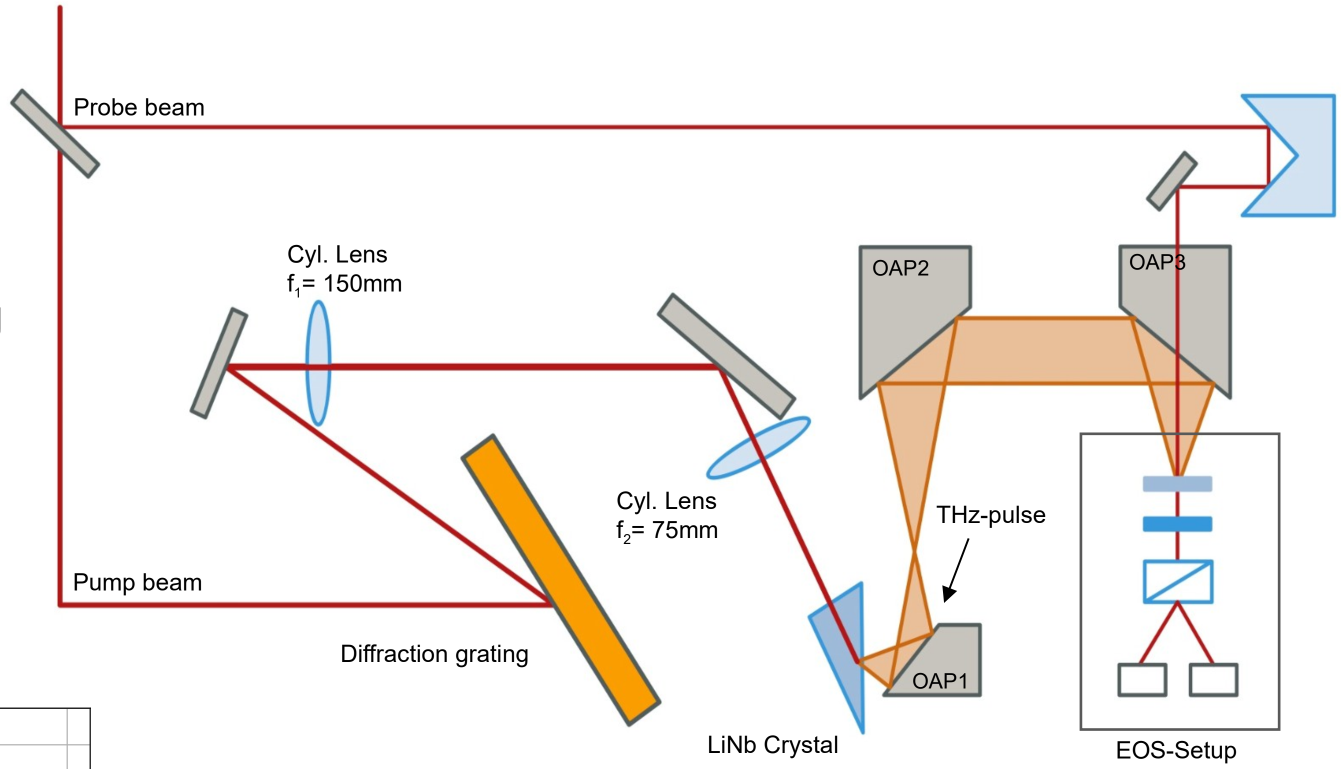
Tilted Pulse Front Setup

For Generation of broad band single-cycle THz-pulses

- Generation of THz-pulses by optical rectification of femtosecond laserpulses in $LiNbO_3$
- Lasersystem: 40 fs Ti:Saph
- Pulse Characterisation with electro-optic-Sampling Setup using balanced detector method,
- Spectrum goes up to 1.5 THz
- Conversion efficiency η = 0.56%
- Max. Pulse Energy E = 17.44 µJ



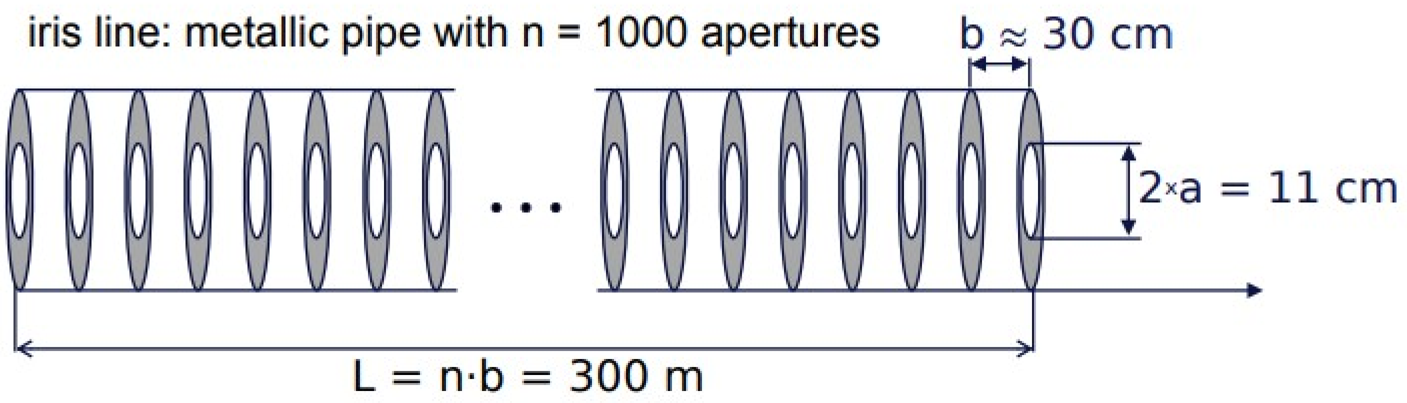




THz transport

Iris line

iris line: metallic pipe with n = 1000 apertures

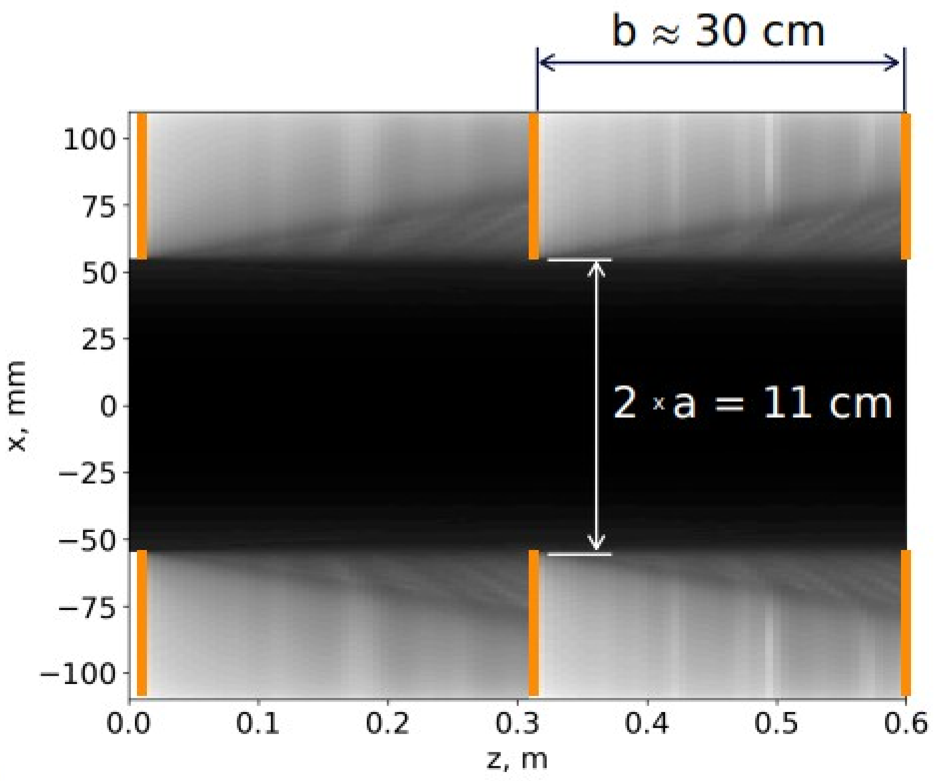


all errors are random (gaussian distribution)

a radius	a displacement	line displacement	b
< 1 mm	< 1 mm	< 1 mm	< 10 mm*

overall line bends

*no systematic error



Courtesy investigation by Andrei Tribushinin.

Lasing in a DLW - Possibility for experiment at AREAL

Achieving a very compact high-power THz source

- Can the wakefields produced in a waveguide act back onto the electrons at low energy to reorganize the electrons (gain) the electrons within a waveguide?
- This was actually explored long ago with low-brightness beams (microtrons)
- The results were promising for the available technology.
- In 2015, Stupakov published a theory paper on the concept, having ignored previous work from Walsh+

VOLUME 66, NUMBER 6 PHYSICAL REVIEW LETTERS 11 FEBRUARY 1991

Observation of Coherent Millimeter and Submillimeter Emission from a Microtron-Driven Cherenkov Free-Electron Laser

F. Ciocci, A. Doria, G. P. Gallerano, I. Giabbai, M. F. Kimmitt,[a] G. Messina, and A. Renieri,
Dipartimento Sviluppo Technologie di Punta, Comitato Nazionale per la Ricerca e per lo Sviluppo dell'Energia Nucleare e delle Energie Alternative (ENEA), Centre Ricerche Energia Frascati, C.P. 65-00044 Frascati, Rome, Italy

J. E. Walsh
Department of Physics and Astronomy, Dartmouth College, Hanover, New Hampshire 03755
(Received 19 October 1990)

We report the observation of coherent emission from a Cherenkov free-electron laser driven by a 5-MeV radio-frequency microtron. Power up to 50 W in pulses of 4-μs duration has been generated at the wavelengths of 1.6 and 0.9 mm using two different dielectric-loaded waveguides.

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **18,** 030709 (2015)

Using pipe with corrugated walls for a subterahertz free electron laser

Gennady Stupakov*
SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA
(Received 1 January 2015; published 18 March 2015)

A metallic pipe with corrugated walls supports propagation of a high-frequency mode that is in resonance with a relativistic beam propagating along the axis of the pipe. This mode can be excited by a beam whose length is a fraction of the wavelength. In this paper, we study another option of excitation of the resonant mode—via the mechanism of the free electron laser instability. This mechanism works if the bunch length is much longer than the wavelength of the radiation and, hence, does not require bunch compression. It provides an alternative to excitation by short bunches that can be realized with relatively low energy and low peak-current electron beams.

Lasing in a DLW

Theory basics and example from Stupakov

- Gennady's paper uses a simple example, 5 MeV, 100 A beam in a corrugated (same to DLW) waveguide.
- The waveguide is 340 GHz with group velocity of 0.05c
- Leads to gain length of 7 cm, and saturation power of 6.7 MW.
- Further optimizations for different energies could be explored
- He further mentions that by tweaking various parameters the gain length can be reduced to 5.5 cm
- Important to also mention that the gain length is proportional to energy. (but so is possible extracted energy!)

TABLE I. Corrugation and beam parameters.

Pipe radius (mm)	2
Depth h (μm)	50
Period p (μm)	40
Gap g (μm)	10
Bunch charge (nC)	1
Energy (MeV)	5
Bunch length (ps)	10

Thanks