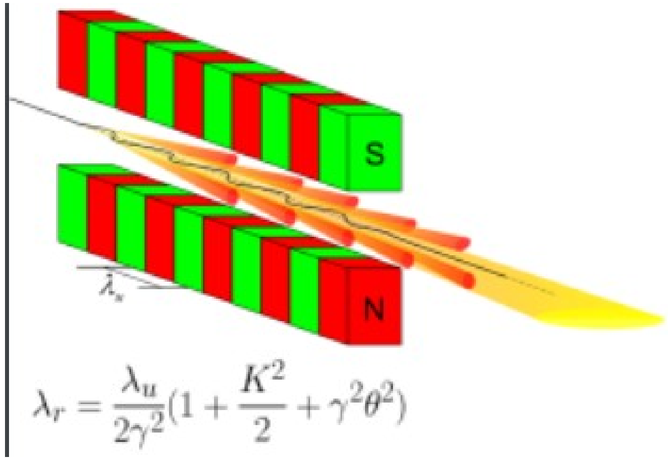
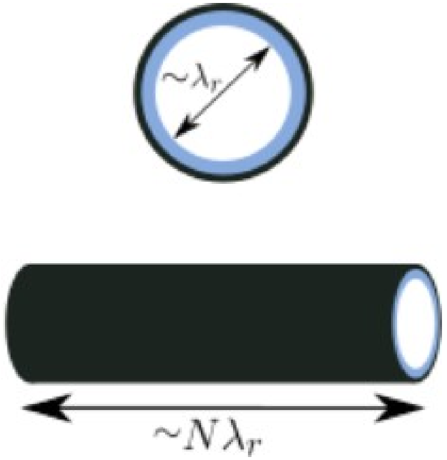
Overview of STERN, goals and requirements

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 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
    - Challenging synchronization for high frequencies, likely impossible with laser based sources.

Electron beam based radiation sources

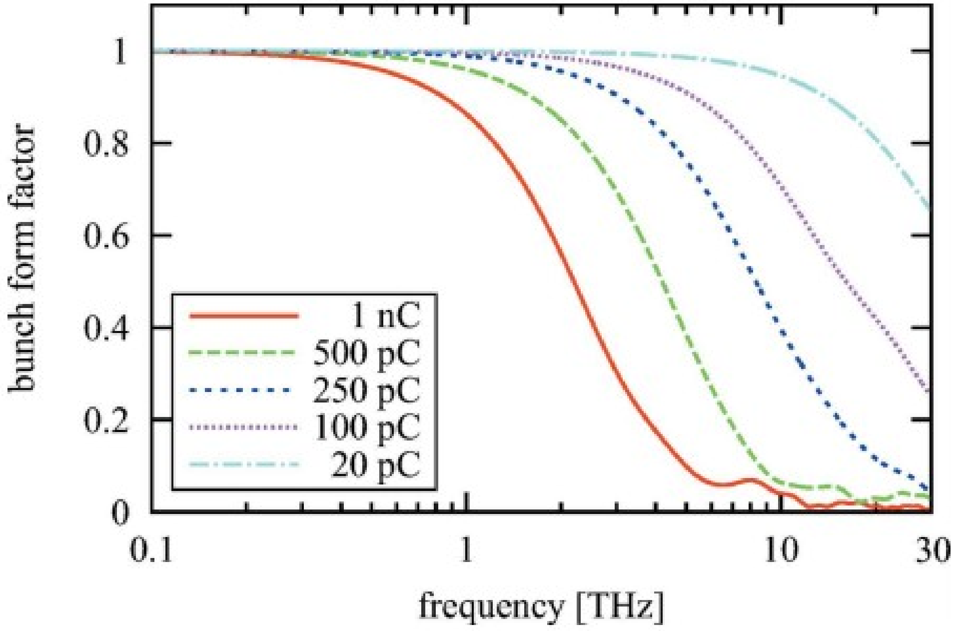




- Undulator approaches are used conventionally but strongly depend on beam energy (m for 18 GeV)
- In contrast Cherenkov approaches are energy independent and depend on structure dimensions
- The wakefield energy scales as $E^{\mathrm{rad}} = q^2 F^2 |K_{\parallel}| L = q^2 F^2 L \frac{Z_0 c}{2\pi r_1^2}.$
- And the power scales as: $P^{\mathrm{rad}} = q^2 F^2 \frac{Z_0 k_0^2 c}{16\pi}.$
  - 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, F, Lemery, M. Dohlus, M. Marx, V. Tsakanov, M. Ivanyan *J. Synchrotron Rad.* (2021) **28**, 18-27 for details.

Spectral content of the XFEL operational modes

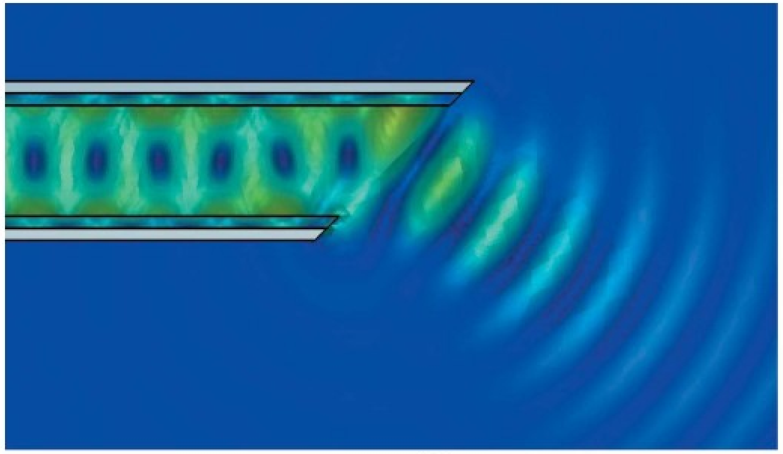
- Motivated to develop Superradiant THz generation at XFEL (STERN), for R&D starting in 2025.
- The XFEL's operational modes and their corresponding bunch form factors are shown right.
- Example cases:
  - For 100 GHz, a 2 mm inner radius would support the production of 3 mJ over a 66 cm long structure for 1 nC.
  - For 6.6 THz, a 1 mm inner radius would support the production of 0.7 uJ for a centimeter long structure at charges between 0.1-1 nC.
  - Energy requirements falling off quickly at higher frequencies, only 300 nJ required at 10 THz. (Assuming focusing THz to diffraction limited spot size.)

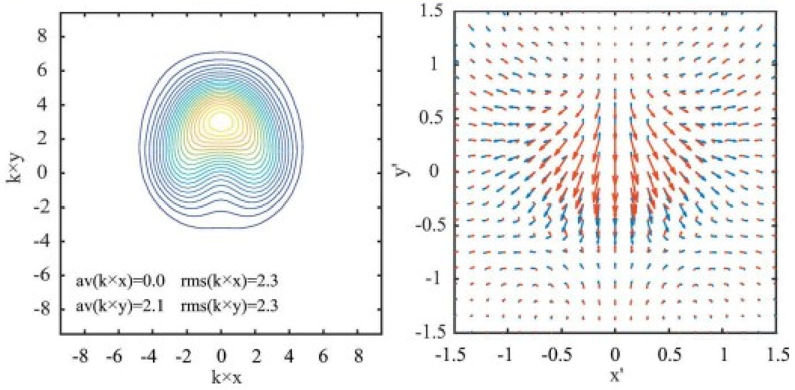


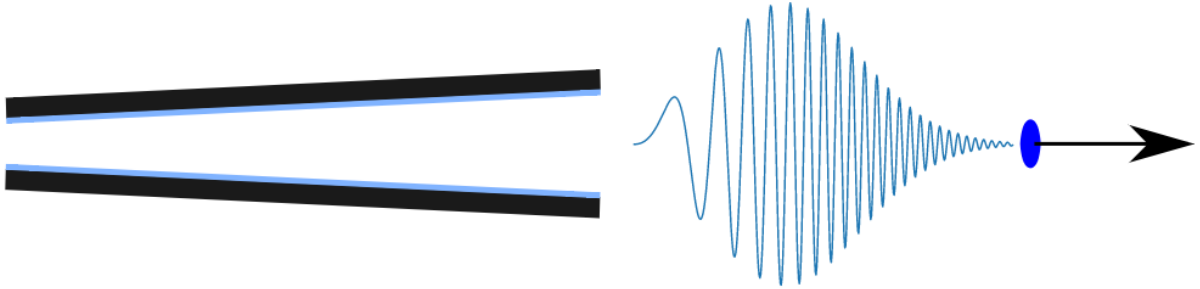
Outcoupling and limitations

Short-bunch production and applications

- Vlasov antennas are especially attractive to outcouple radiation, allowing for a separation between electron beam and THz.
- Here is a concept of how Vlasov antennas could be integrated and outcoupled to the diagnostics table.
- Simulation (right) done by M. Marx and M. Dohlus.

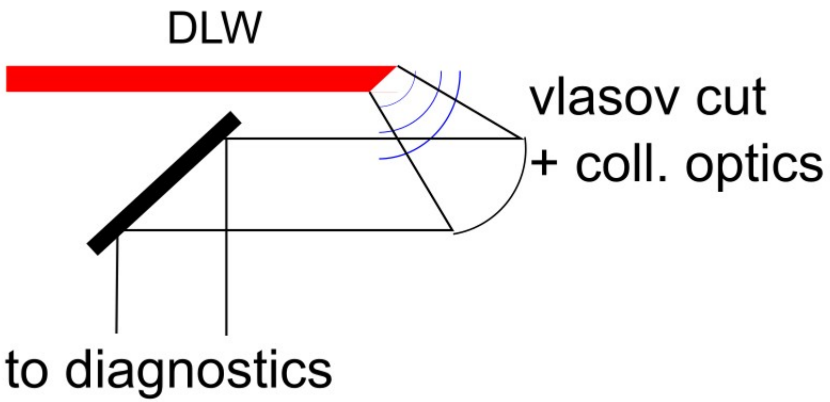






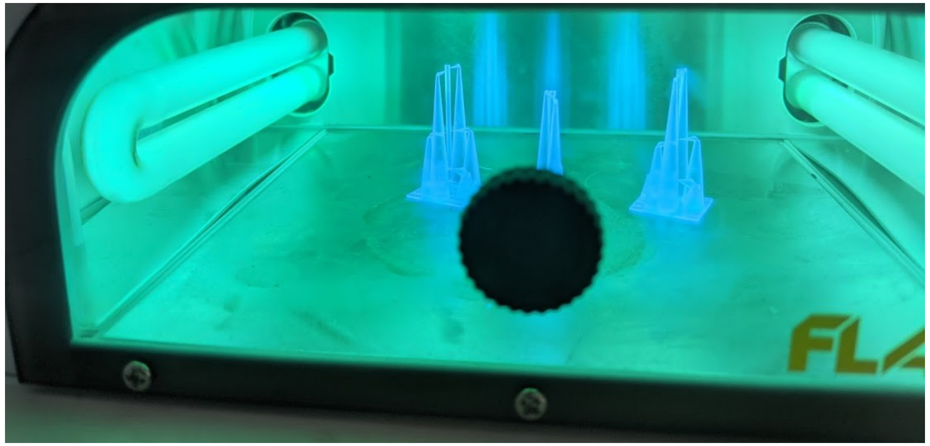
Under study: chirped structures for the production of chirped THz pulses

- in combination with frequency filters to generate different colors
- in combination with a pulse compressor to reduce the pulse length and increase the power.



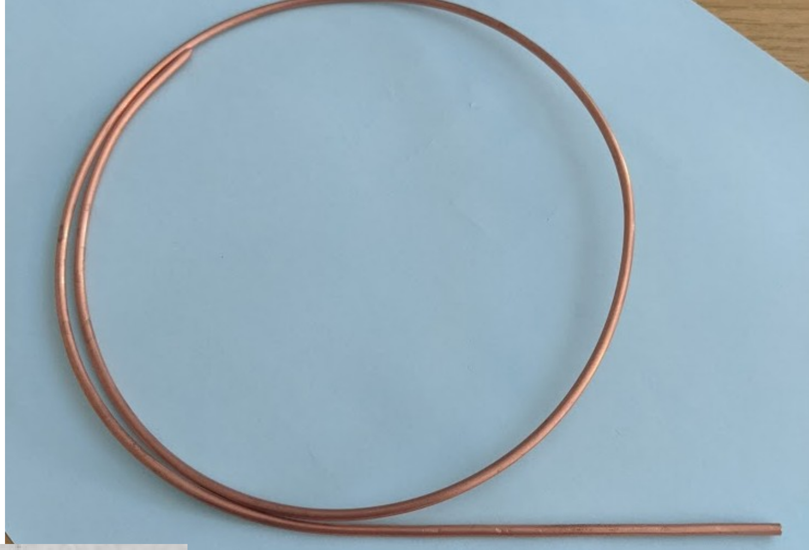
THz structures and development

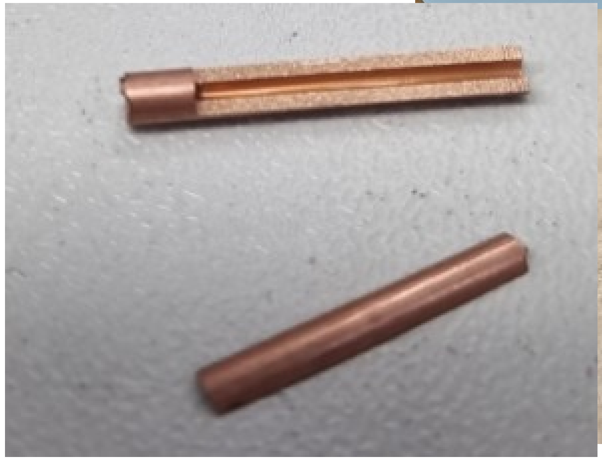
- Currently investigating several types of waveguides: dielectric lined, corrugated, and bi-metallic (Armenians colleagues).
- Corrugated structures are more challenging to produce in cylindrical symmetries, while dielectric and bimetallic waveguides can be produced more easily
  - Dielectric e.g. fused silica can be drawn and coated
  - Dielectrics can also be deposited with gas or oxidation
  - Metallic surfaces can also be deposited.
- We are also pursuing 3D printed waveguides and now with an external company in HH, DMG, trying to develop low-loss THz resins.
- Finally, we are also interested in photonic bandgap crystals fibers.

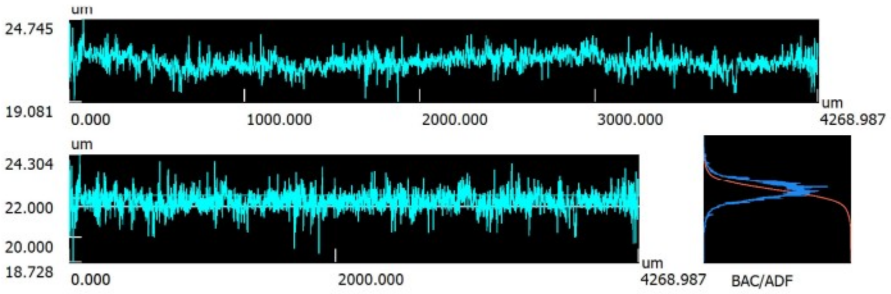


Drawn copper capillaries

- Clemens 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.



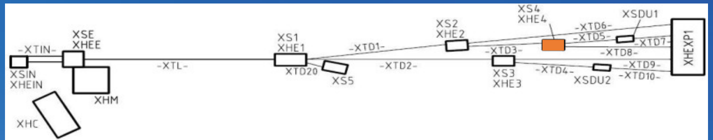




surface roughness (ZMQS)

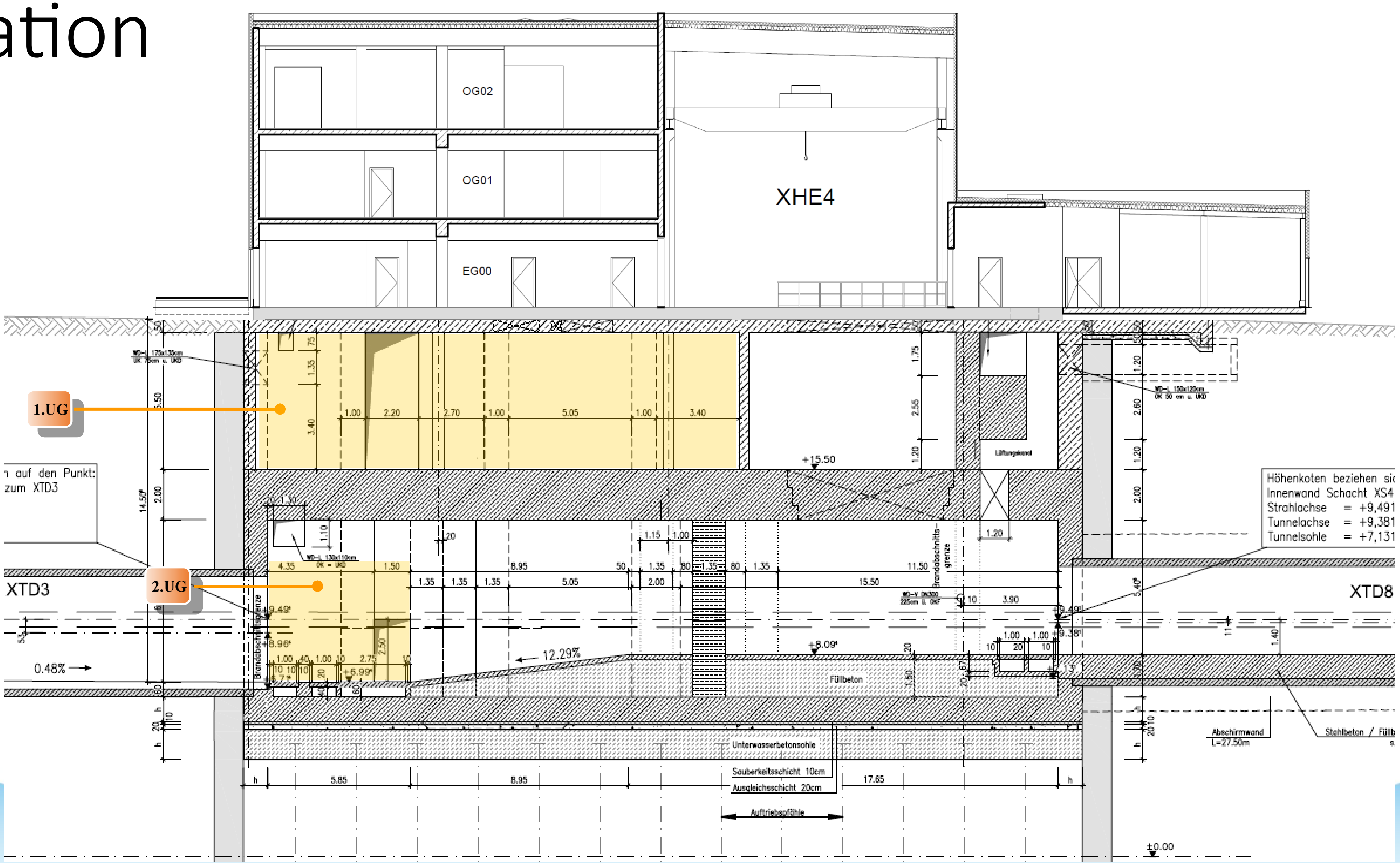
Details

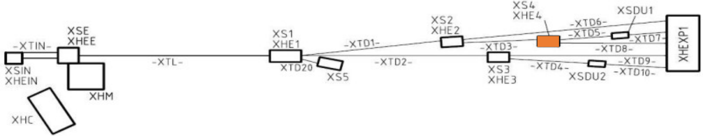
- Location approximately z=2950 (XS4)
- Interested in symmetric beta function of beta_x=beta_y ~ 1 m (if possible).
- Need also to ensure proper conditions for BD+
- The two star locations will represent the THz generation location and detection. Which can be upgraded to transport to users.



XS4 / XHE4 Overview

Location





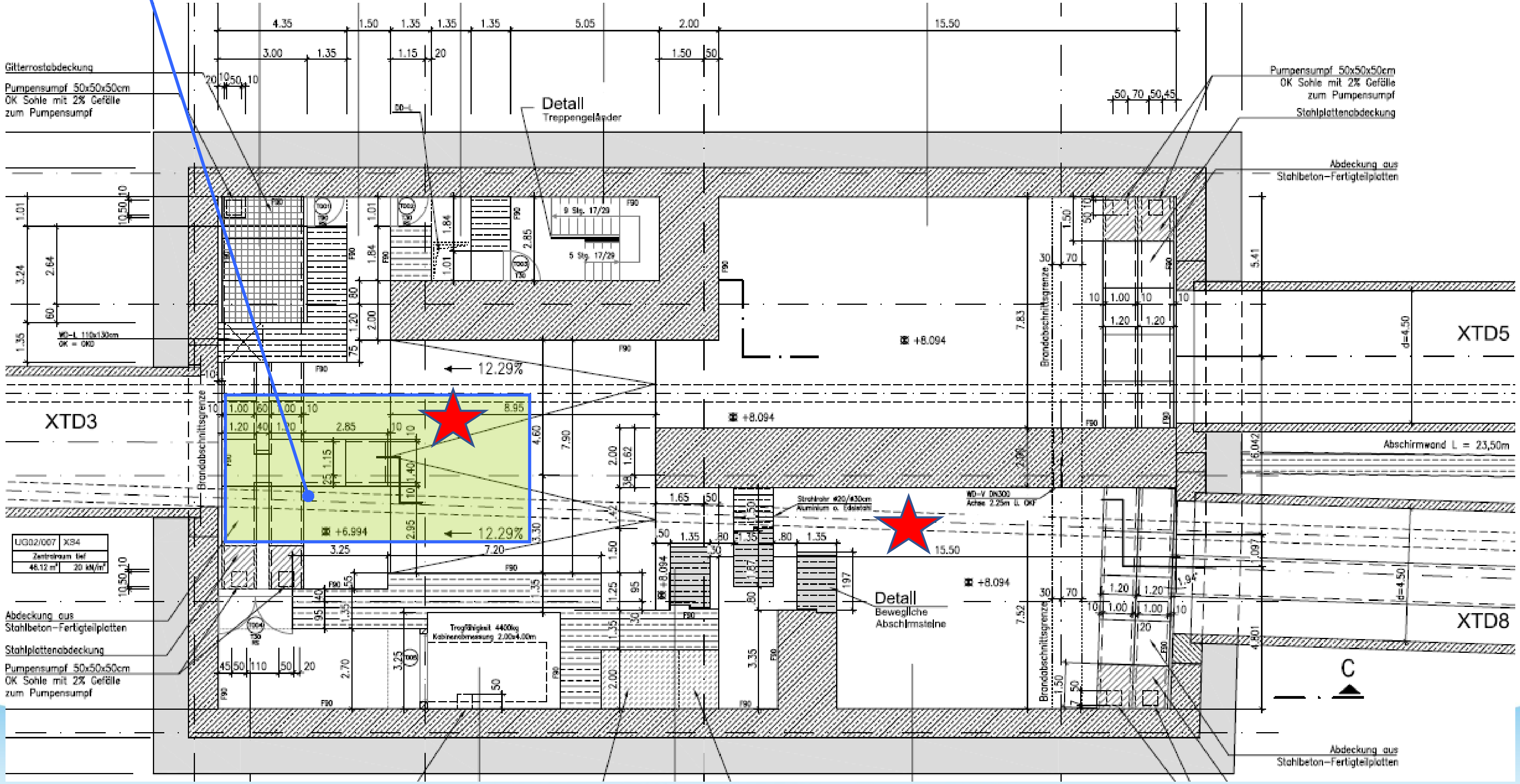
2UG
(Level -2)

XS4

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

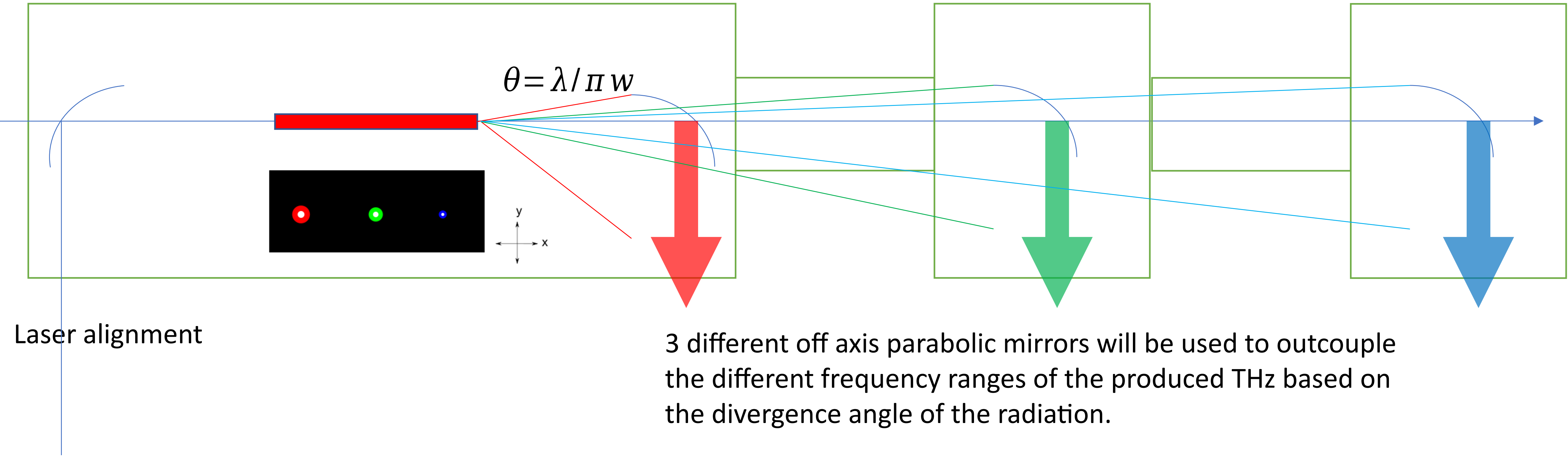
2 Electronic racks

WP17 Standard diagnostics
Responsible: M. Steckel, K Wittenburg



Chamber sketch

Cooling / cold finger connection to tubes



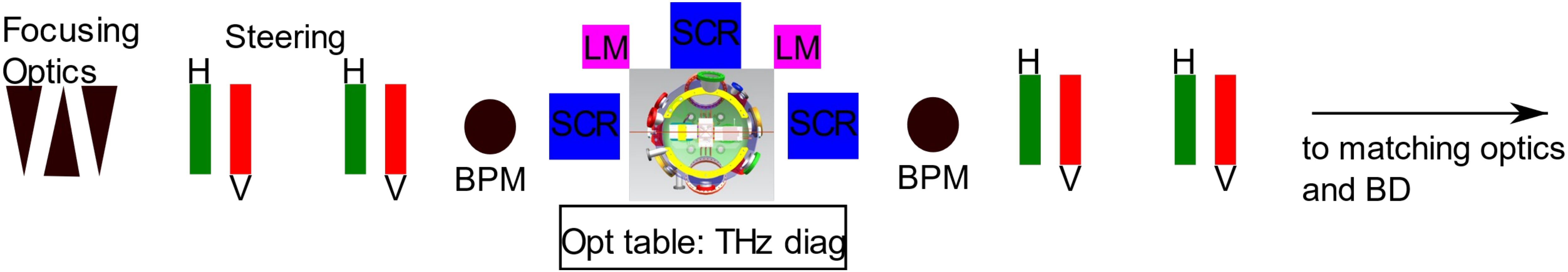
Laser alignment

3 different off axis parabolic mirrors will be used to outcouple the different frequency ranges of the produced THz based on the divergence angle of the radiation.

Rough vacuum chamber to catch THz before transport to XTD8.
Also provides way to catch alignment laser from XTD8

Preliminary layout *idea* 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



Discussion / Diagnostic requirements

- Small aspect ratio structures (1 mm diameter <> 50 cm length)
- Beam position with respect to structure center important, off-axis enables coupling to dipole modes.
- Beam size is about 1 micron at structure. Can we measure this?
- Beam losses somewhat important, will determine if we can use large number of bunches. Cooling foreseen for structures.