Towards large THz fields at the European XFEL

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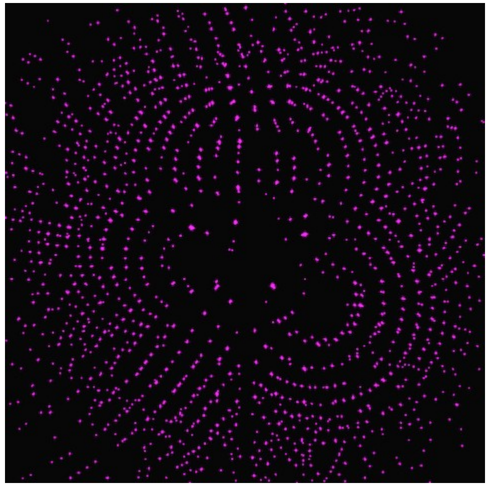
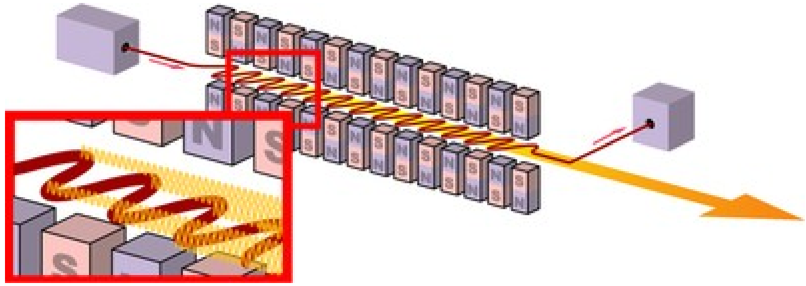
Applications

Light sources

- High-quality electron-based light sources now routinely provide coherent high-energy X-rays (>10 keV) for molecular imaging.
  - This has unveiled a research path toward femptochemistry, enabling a larger understanding of molecular interactions
  - Also is directly providing a path toward understanding complicated biological systems at the nanometer scale.
- Future generation light sources aim to generate TW+ powers to directly image single molecules (e.g. without crystals).





Radiation generation with charged beams

Beam-based THz/MIR production for high-repetition rate facilities

- Modern high-repetition rate XFELs seek THz/MIR sources for pump probe experiments.
  - P. Zalden et. al. Terahertz science at european xfel. (REPORT-2018-002. XFEL.EU TN-2018-001-01.0), 2018.
-
- Large pulse energies are required e.g. 3 mJ for 100 GHz radiation, which is very challenging for laser-based approaches where conversion efficiencies are limited to <1%.
- Beam-based undulator methods have been proposed, but at large beam energies (~10 GeV), the required undulator periods are very large, and complex.
- PITZ has suggested development of standalone SASE to produce THz for XFEL. Also very complex solution.
- Alternatively, wakefields produced Cherkenov waveguides from charged beams *could* potentially produce all requested THz/MIR beam parameters (0.1-30 THz)
  - Many interesting structures to consider: DLW, corrugated, PCF, ARF, etc.

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

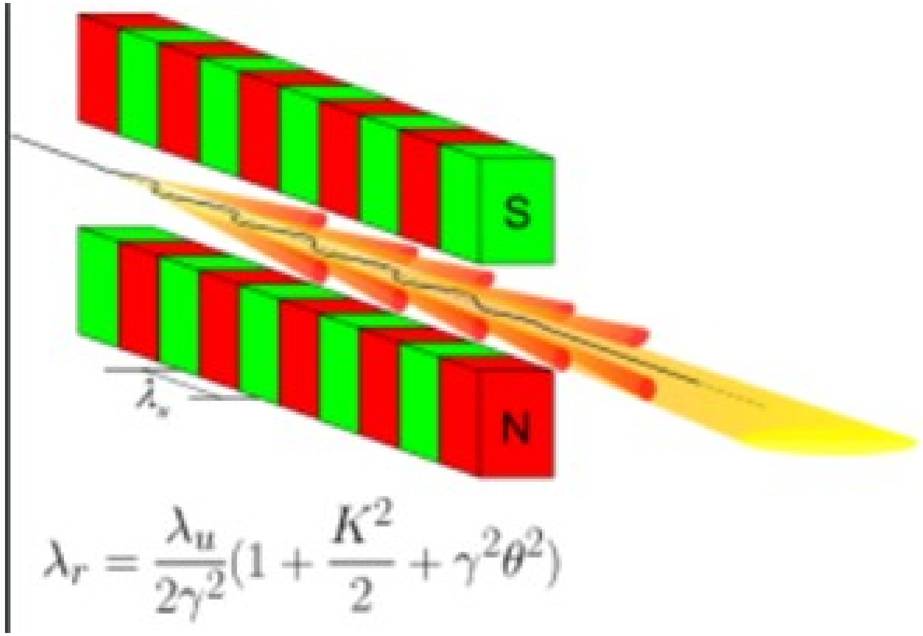
Radiation generation with waveguides

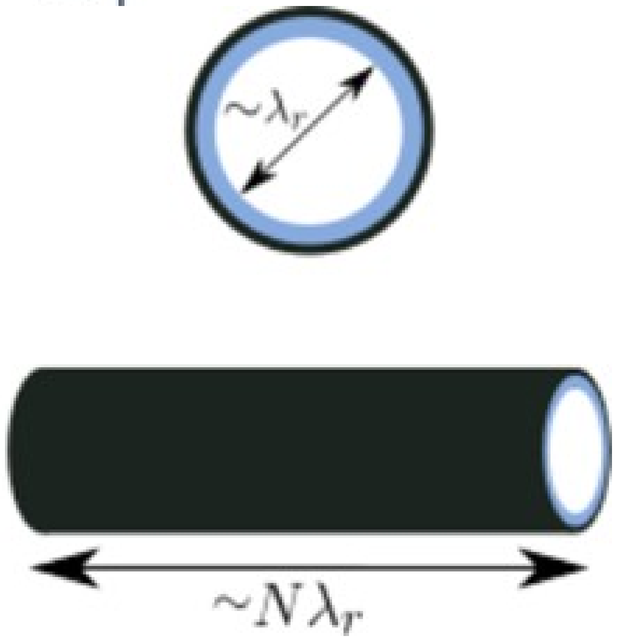
- Dielectric-lined waveguides support modes with phase velocities equal to the speed of light
- Simple formula describes energy produced in waveguide
- For more info, see:

M. I. Ivanyan, L. V. Aslyan, K. Floettmann, F. Lemery, and V. M. Tsakanov. Wakefields in conducting waveguides with a lossy dielectric channel. Phys. Rev. Accel. Beams **23**, 041301 (2020).

K. Floettmann, F. Lemery, M. Dohlus, M. Marx, V. Tsakanov, M. Ivanian, “Superradiant Cherenkov-Wakefield radiation as a THz source for FEL facilities,” *Accepted Journal of Synchrotron Radiation*

$$\mathcal{E} = q^2 F^2 \kappa L = q^2 F^2 L \frac{Z_0 c}{\pi r_1^2},$$

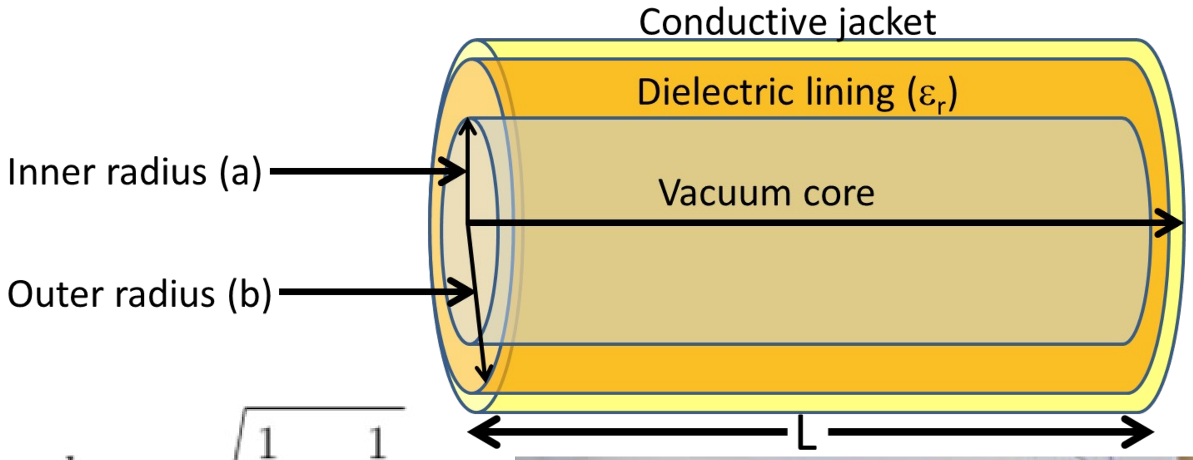




Overview

Dielectric-lined waveguides

- Dielectric-lined waveguides (DLW), corrugated metallic structures, and plasmas are high-impedance mediums - leading to a wide variety of beam-related applications:
  - Acceleration
  - Beam manipulation
    - De-chirping
    - Microbunching
    - THz generation
    - Streaking
  - The basis for these techniques relies primarily on the TM mode
  - *Note: The fundamental mode is a deflecting mode!



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

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

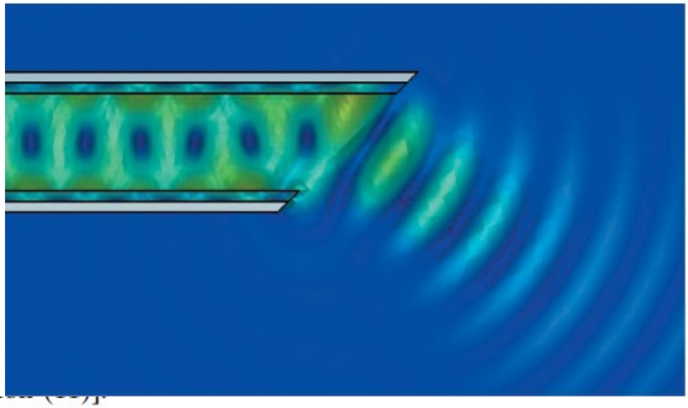
$$k_z = \frac{\omega}{v_p}.$$

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

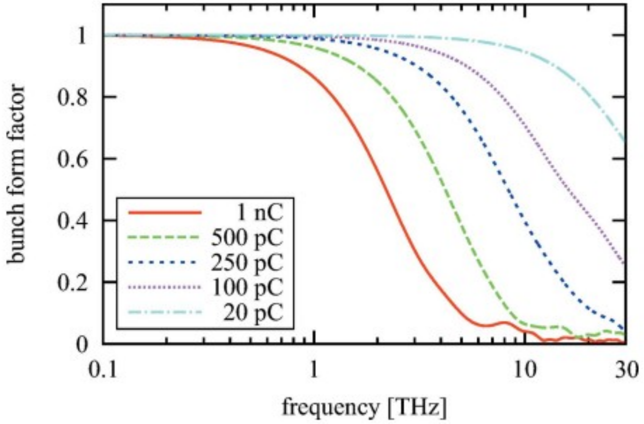
$$E_r = \begin{cases} \frac{-ik_z}{k_1} B_1 J_0'(k_1 r) e^{i(\omega t - k_z z)} & 0 \leq r < a \\ \frac{-ik_z}{k_2} B_2 F_{00}'(k_2 r) e^{i(\omega t - k_z z)} & a \leq r \leq b \end{cases}$$

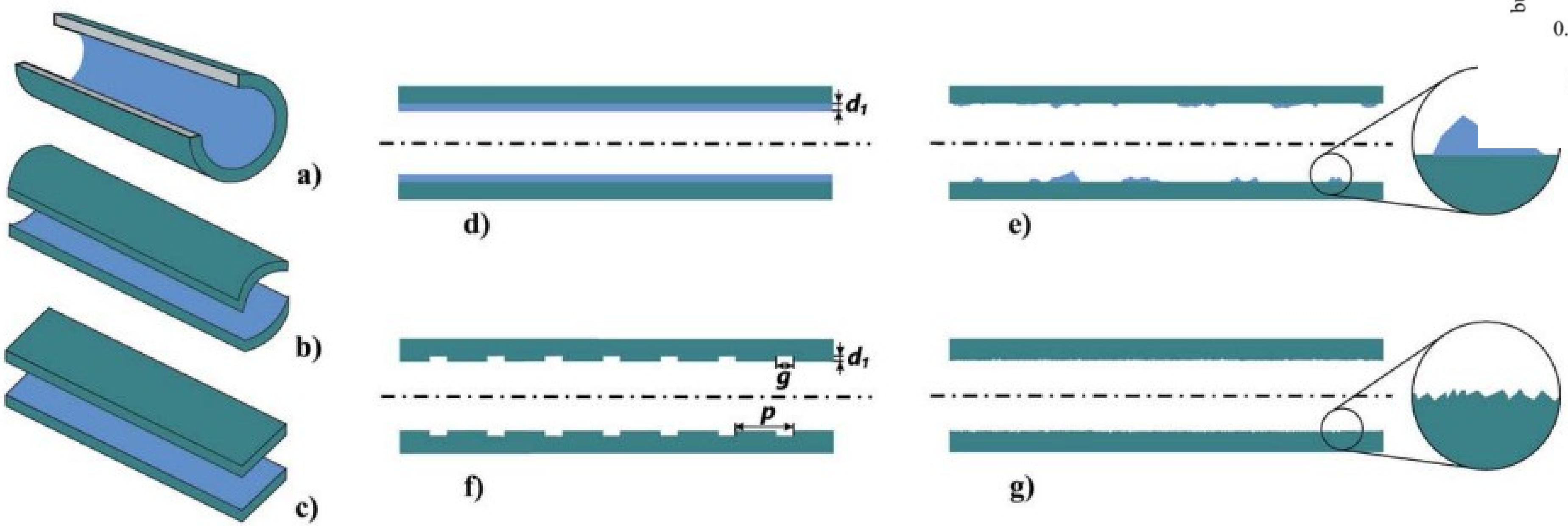
$$H_\phi = \begin{cases} \frac{-i\omega\epsilon_0}{k_1} B_1 J_0'(k_1 r) e^{i(\omega t - k_z z)} & 0 \leq r < a \\ \frac{-i\omega\epsilon_r\epsilon_0}{k_2} B_2 F_{00}'(k_2 r) e^{i(\omega t - k_z z)} & a \leq r \leq b \end{cases}.$$

Wakefield R&D



- Aim to investigate several types of structures to cover full frequency range.
- Also interested in developing waveguides with ‘tunable’ frequency ranges.
- Heating must also be investigated but rough calculation suggests no concern
- Below are examples of large range of available waveguides,
  Dielectric, bimetallic, corrugated, roughness, and geometries
- Other novel geometries under investigation also.

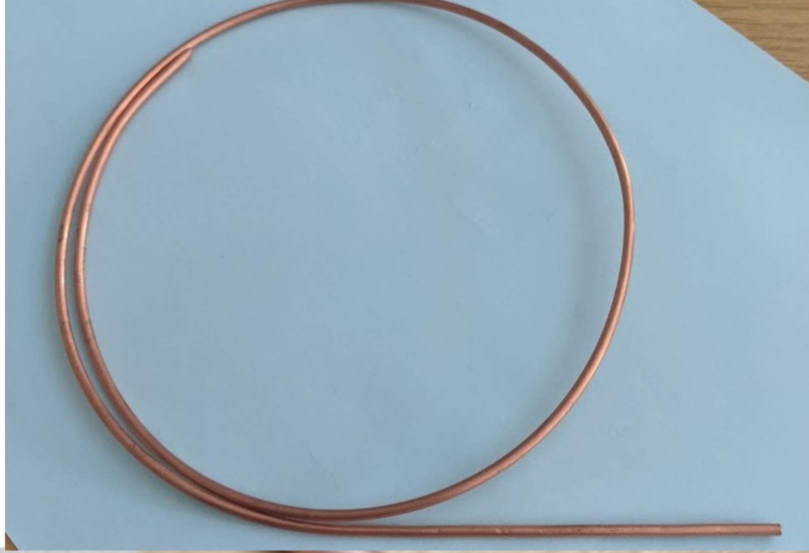




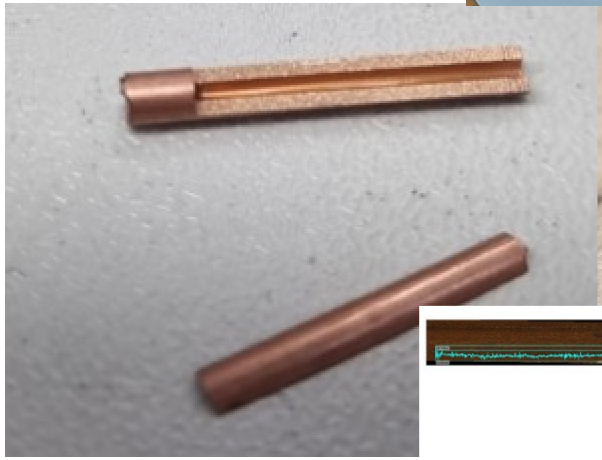
High frequency structures

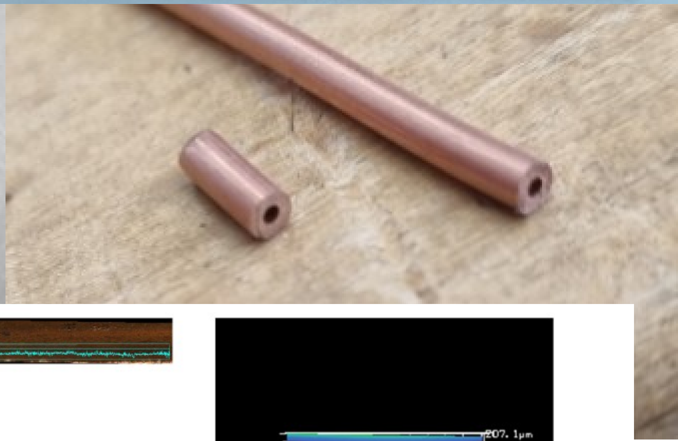
- The low-frequency (< 4 THz) seem manageable and have been measured previously.
- One limiting factor to high frequency wakes (10+ THz) is the conductivity of copper or metallic substrate or surface.
- Another is the surface roughness of the metallic surface. This roughness leads to an effective mode definition, e.g. corrugated structure.
- There are several options to be investigated:
  - Copper coated ultra thin walled hollowcore fibers.
    - Challenging due to the frailness of such fibers.
  - Drawn copper waveguides with ALD deposition.
    - Here limited by roughness of drawn copper structures. Can be further electropolished also.
    - Now calculating roughness limitations of acquired waveguides.
    - Subsequently will ALD (alumina) the waveguides and check the

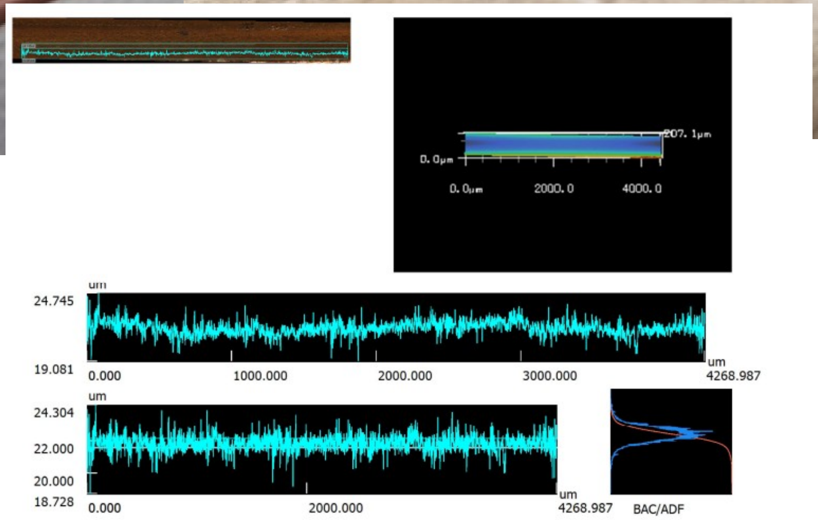
Drawn copper capillaries



- Clemens has made some great progress on cutting these structures
  - Flat/straight cuts
  - Longitudinal/Open cuts
  - Vlasov cuts
- Have started collaboration with R. Zierold (CHyN) to investigate coating.
  - Coating can be realized on very precise levels with many different 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.







ZMQS measurements

Experimental area

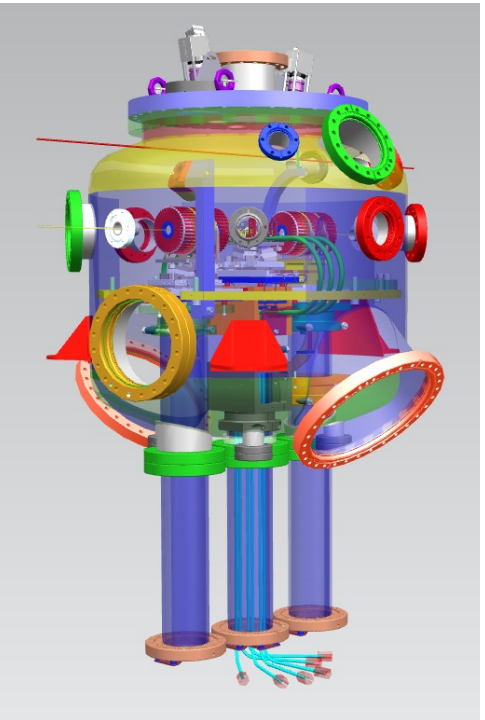
Planning for installation in 2025 at XTD5.

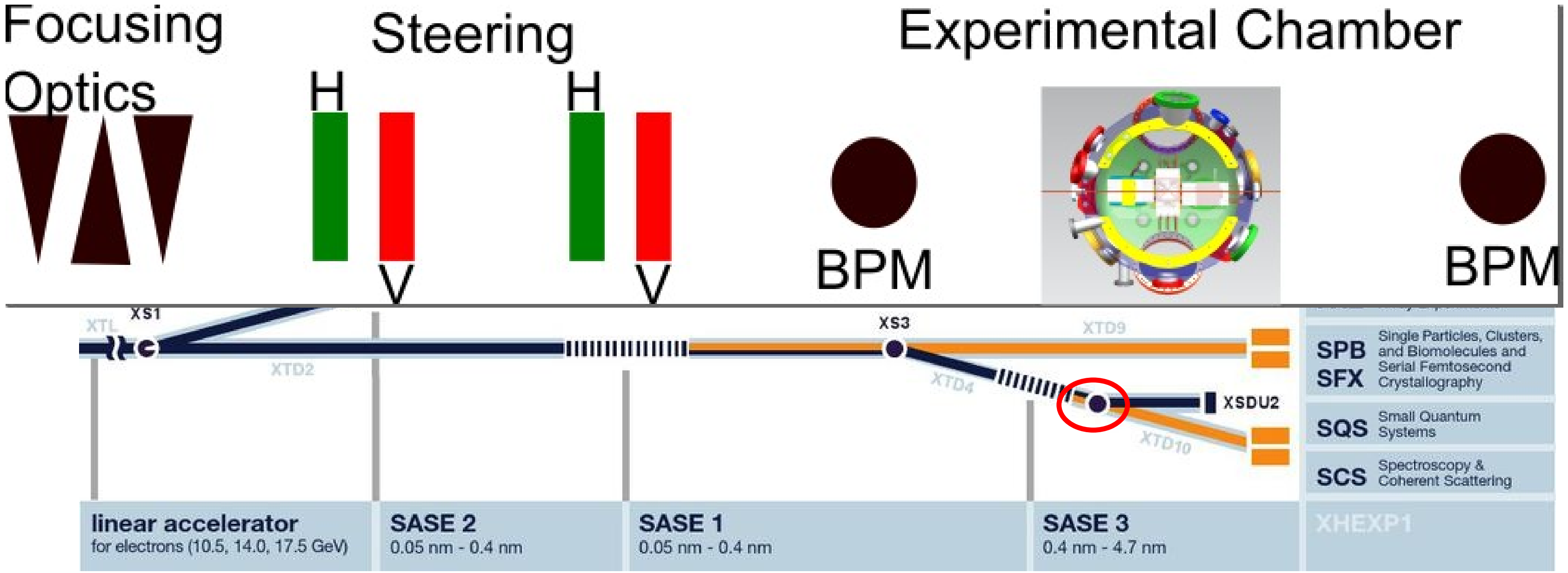
Currently optimizing beam optics to obtain very small beam sizes (~ 1 micron full width), to procure suitable magnets, and equipment.

Current solution uses 4 new quadrupoles.

Not very trivial since beta functions at the beam dump are 200 km.

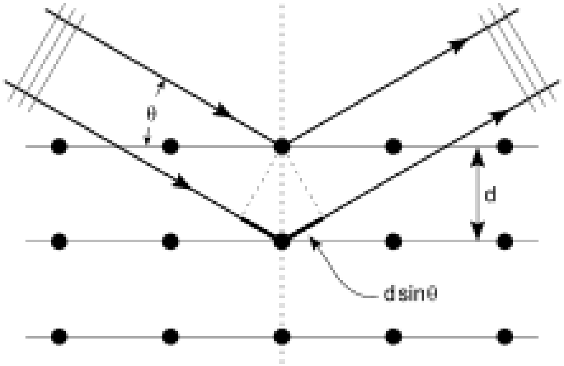
Radiation generation studies ongoing, will also begin study on beam transport to users 300 m away.



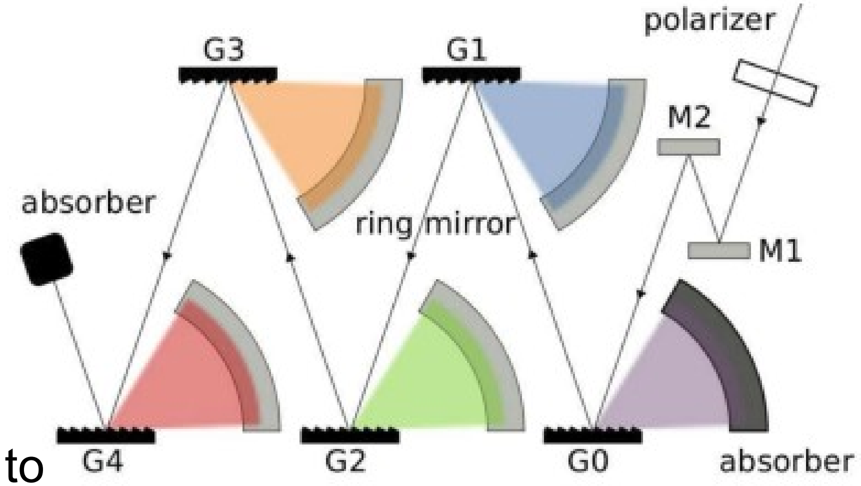


Synchronization

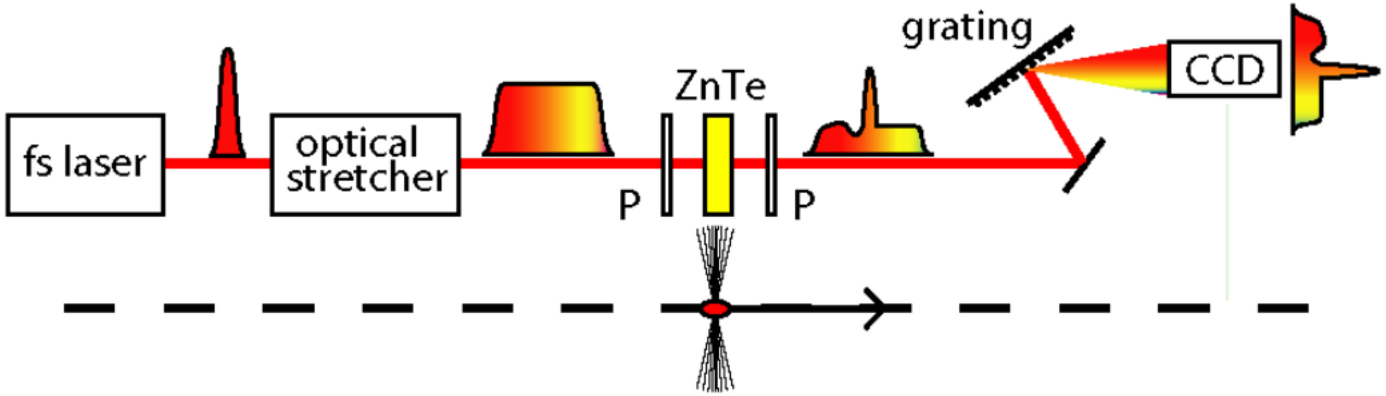
- Synchronization is a significant detail to investigate.
- X-rays are generally very difficult to reflect, requiring diamond mirrors with low grazing incidence, especially with high-energies
- Therefore an x-ray delay line in the hard x-ray spectrum is very difficult to implement.
- Alternatively, THz is relatively easy to reflect, especially with gold-coated optics.
- Current approach will be to use a THz bunch with desired injection phase in advanced bucket compared to X-ray pulse.
  - Subsequently a THz delay line will provide appropriate compensation for timing.
  - This also allows independent use of kickers
- This also enables the development of a “THz hutch” where characterization, delay, and compression could be realized before sending to users.



Diagnostics

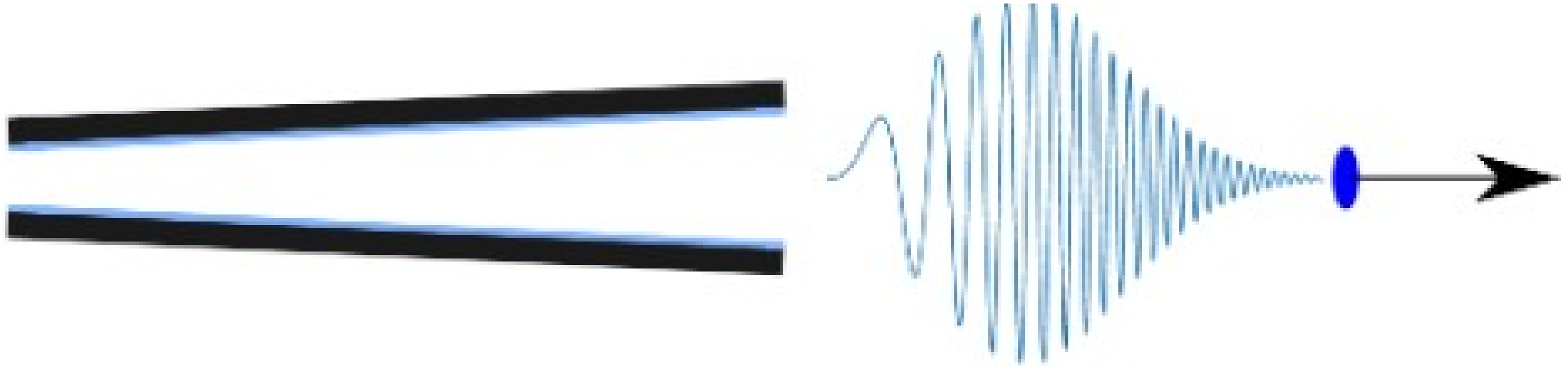


- Investigating several approaches for diagnostics:
- Coherent Radiation Intensity Spectrometer (CRISP)
  - Currently used at FLASH and XFEL, and uses series of gratings to diffract different portions of THz spectrum onto pyro.
  - For further information see work by Lockmann (DESY)
- Alternatively to achieve time signal or e.g. electric field, electro optic sampling (EOS) is possible. This can also be pushed to the single-shot regime by using chirped laser pulses.
  - For further work see, Bernd Steffen (DESY)



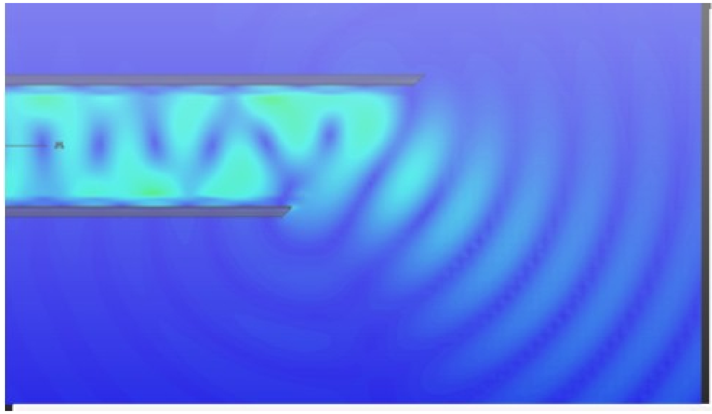
Chirped structures

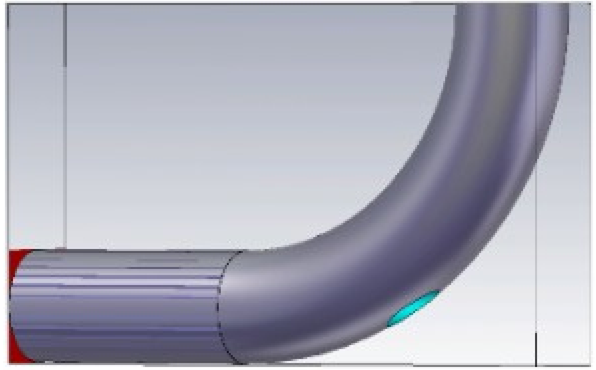
- Looking to investigate chirped structures.
- Here instead of using array of dedicated single mode structures, possibly a single chirped structure could cover a wide range of frequencies.
- By tuning the arrival time of the THz pulses, different frequencies could be used in pump-probe spectroscopy.
- This technique requires knowing if earlier arriving fields would perturb the samples- e.g. what is the relaxing time?



Some possible coupler styles and ideas to consider

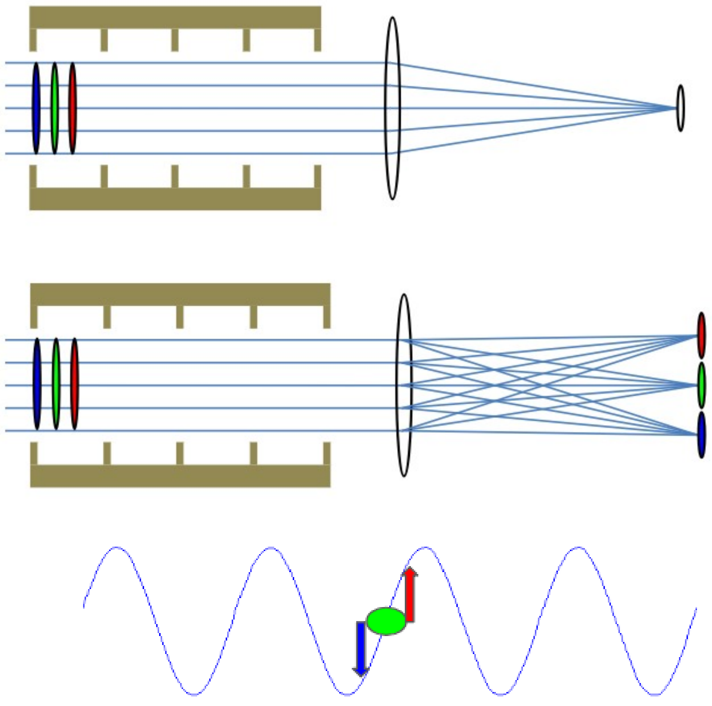
- Now 3D printing capillaries and pushing to develop low-loss (~ e.g. PTFE-like) resins with external company.
- Goal:
  Design a side-coupler for a streaking cavity (HE11 mode) in CST,
  export to .stl file for 3D printer
  print and clean the device
  apply external copper coating via sputtering machine
- Other modes, e.g. TM01, TE01, etc, also very interesting.
- How to develop such couplers, should we implement possibly, machine learning?
- Difficult possibly to print for high frequencies, perhaps room to collaborate with the nanoscribe?





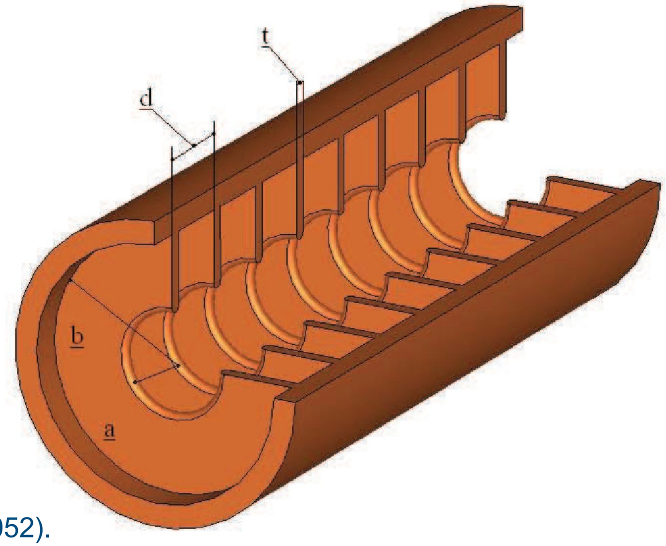
THz streaking with multicycle THz

Overview of transverse deflection structures



- DLWs notoriously have a large dipole mode contribution which leads to BBU.
- Can we use the THz-driven DLWs to produce a TDS?
- A TDS shears a beam transversely, mapping the temporal distribution into space
- A high resolution power 1/R requires:
  - Large integrated voltage, V
  - Short wavelength, large k
  - Large beam size in the structure, σ_y

$$R = \frac{\sigma_{sc,\text{ un-streaked}}}{\sigma_{sc,\text{ streaked}}} = \frac{\sigma'_{TDS,\text{ uncor.}}}{\sigma'_{TDS,\text{ introduced}}} = \frac{\varepsilon}{\sigma_y}\frac{cp_z}{ekV} = \frac{\varepsilon_n m_0 c^2}{\sigma_y ekV}$$



See F. Lemery, K. Floettmann, T. Vinatier, R. Assmann,
"A transverse deflection structure with dielectric-lined waveguides in the sub-THz regime," Proc. IPAC19 (MOPAB052).

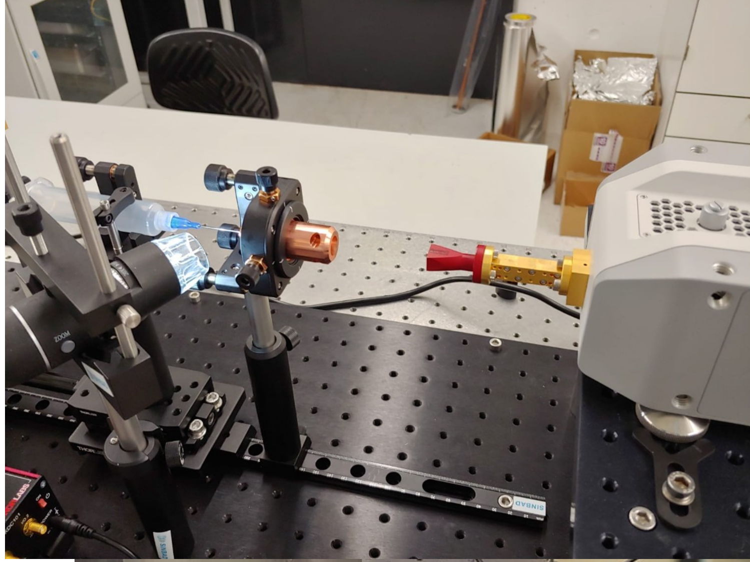
THz streaking with multicycle THz

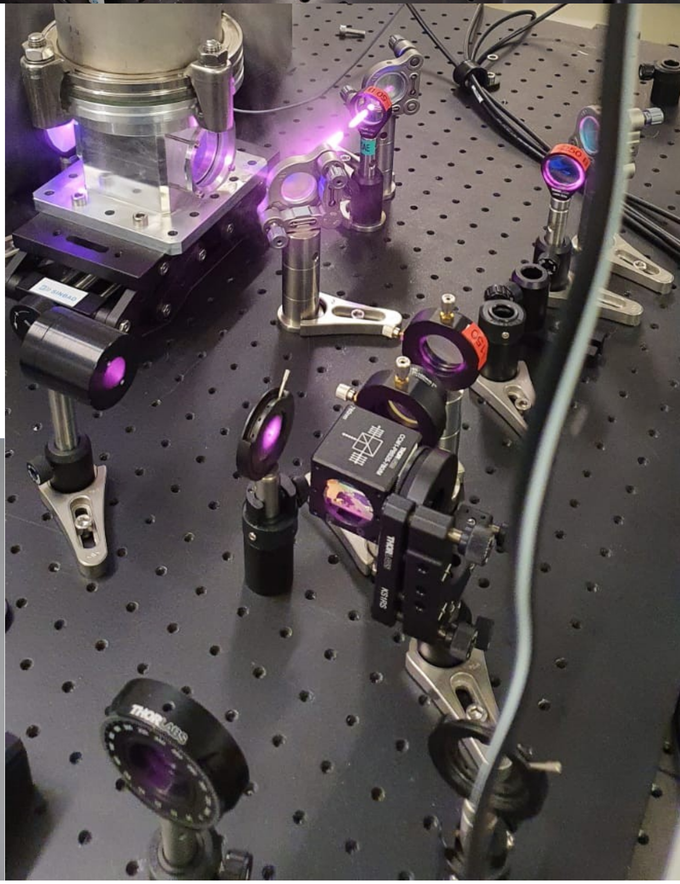
Status of experiment at REGAE

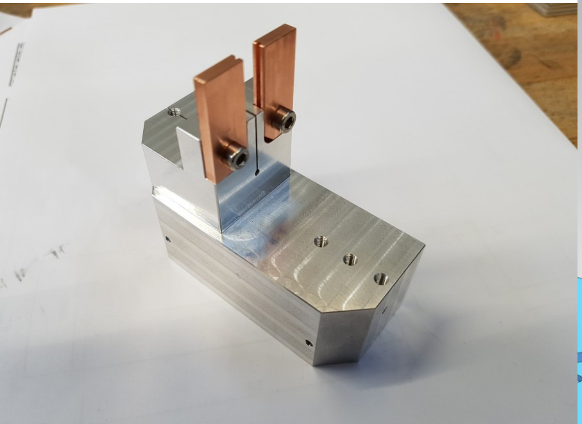
- Structures have been designed, 3D printed, coated, and tested in house.

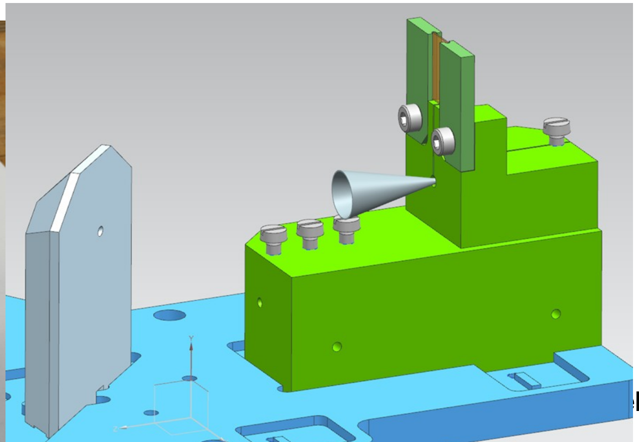
- Currently iterating for final structure based on phase velocity measurements to reduce phase slippage in the structure. See Self-calibration technique for characterization of integrated THz waveguides M. Kellermeier, F. Lemery, K. Floettmann, W. Hillert, and R. Aßmann Phys. Rev. Accel. Beams **24**, 122001 – Published 6 December 2021

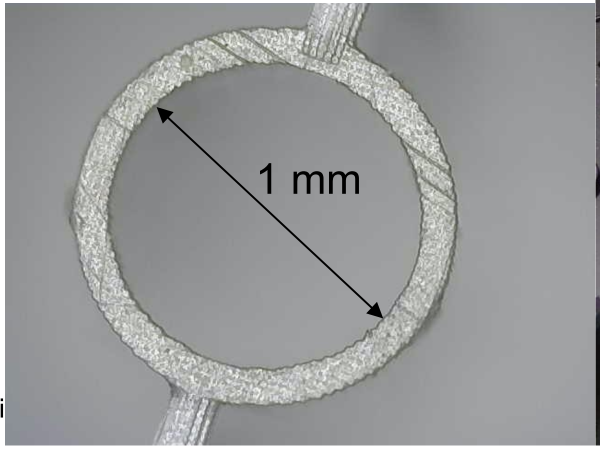
- THz source has works well and is well characterized (EOS) and supports a range of operation from 288-284 GHz (50 cycle pulses).











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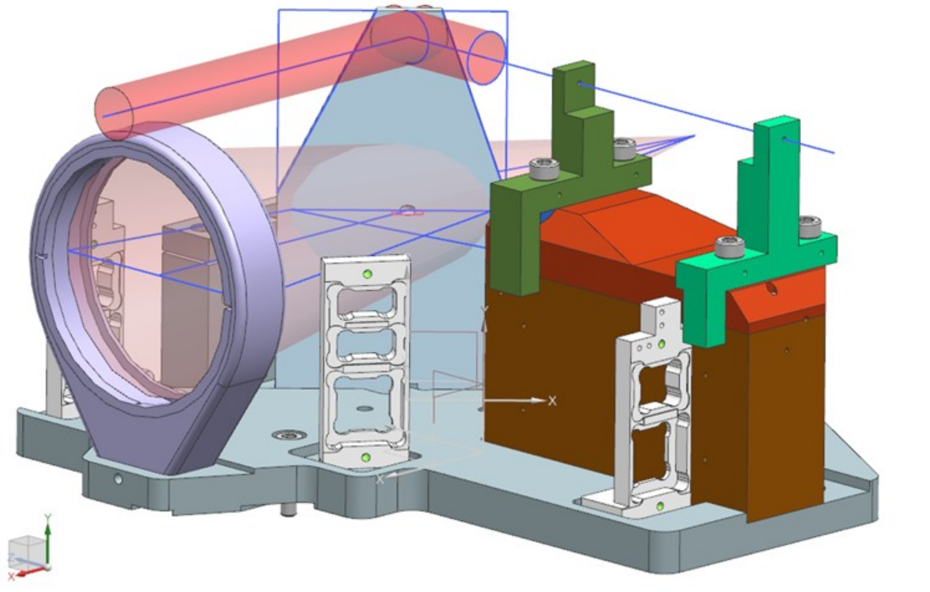
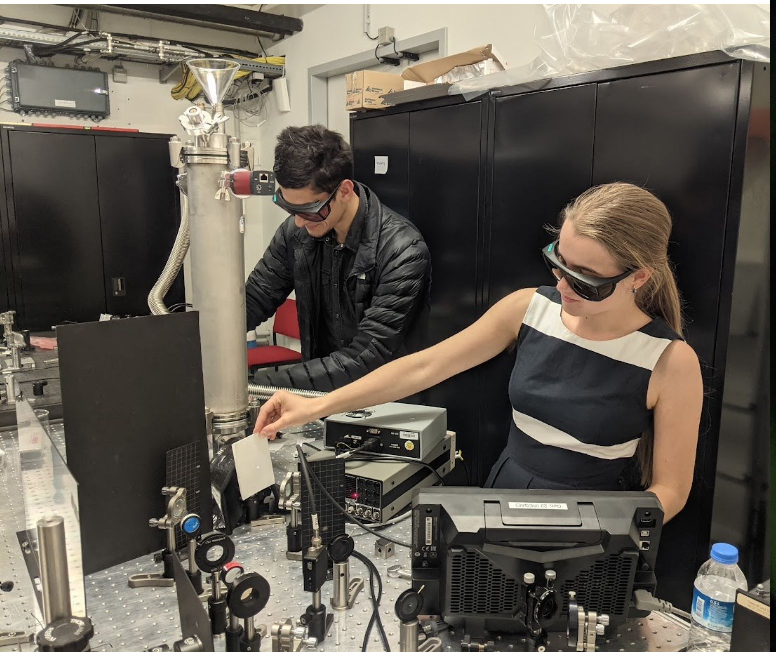
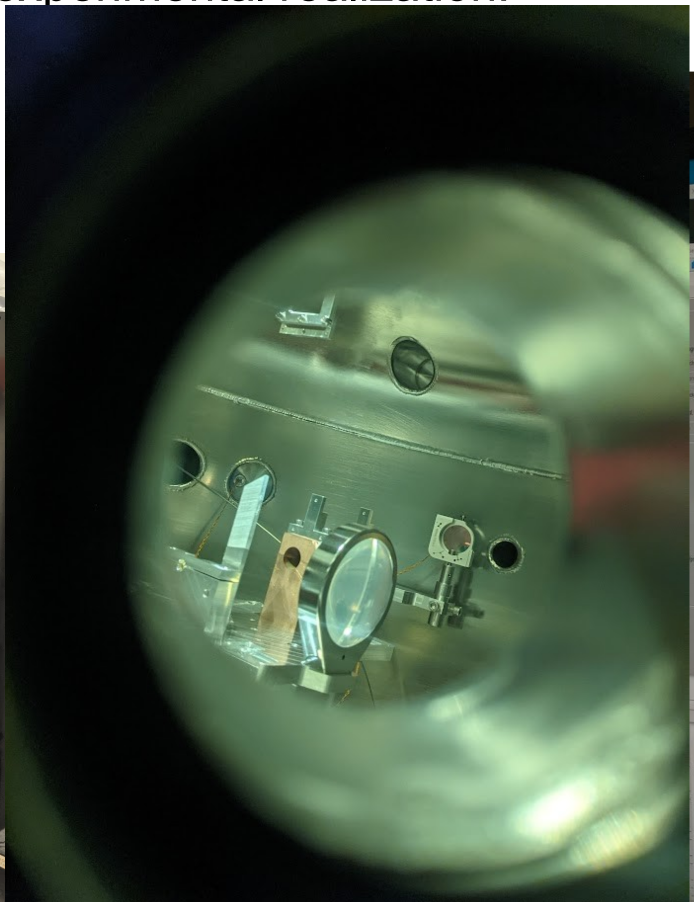
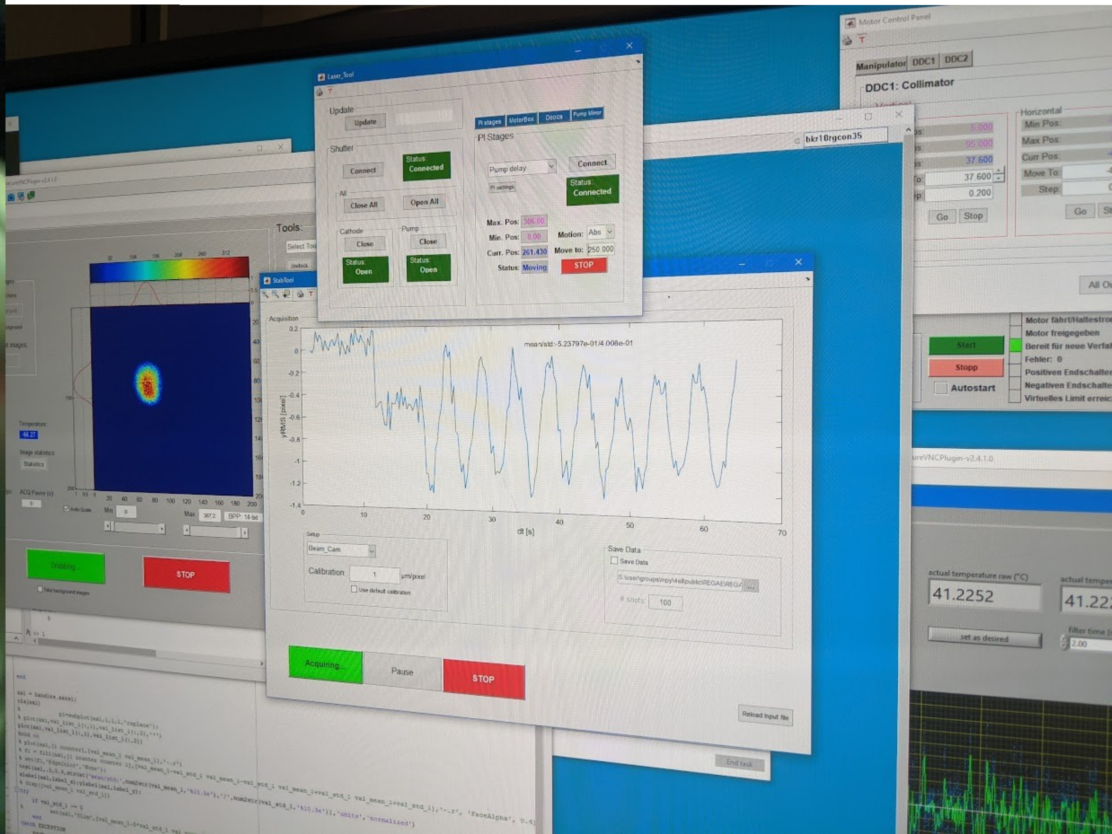
Current status of streaking experiment

- First results obtained, now improving coupling efficiency with new hardware and improving THz source.
- New structure tested with 85% coupling efficiency.
- Now making final steps for experimental realization!









Thank you for your attention!