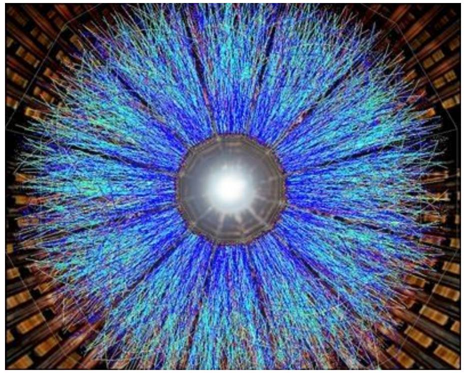
Towards large THz fields at the European XFEL

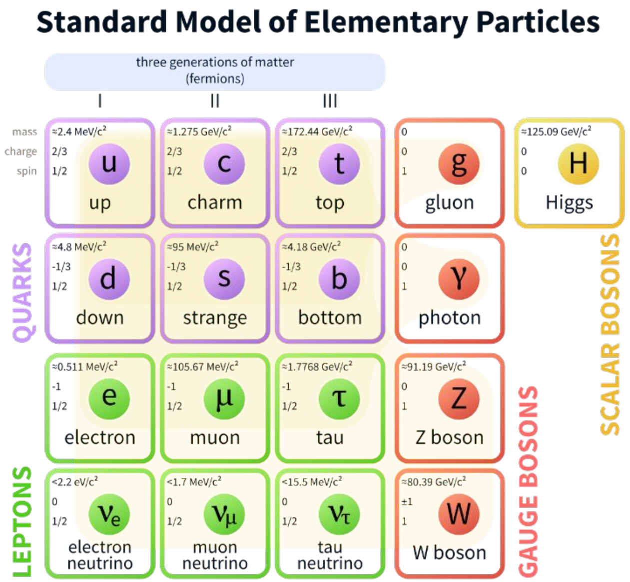
Introducing particle accelerators, applications and novel techniques to support user experiments

Francois Lemery, Klaus Floettmann, Frank Mayet, Max Kellermeier, Ralph Assmann, Luca Genovese, Sven Lederer, Jakob Hauser, Maike Pelzer, Ulrich Dorda, Thomas Vinatier and many others

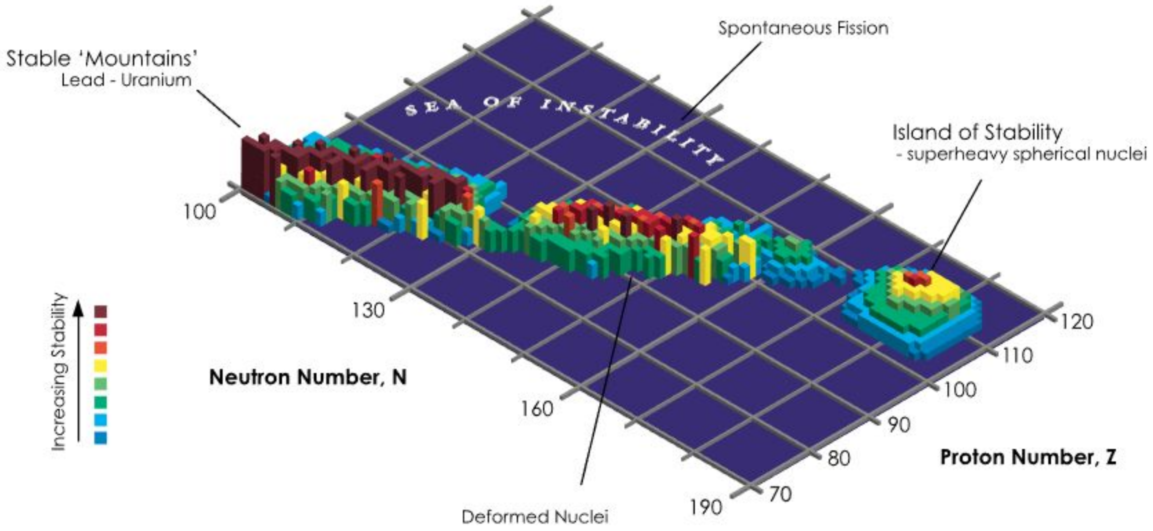
Applications

Colliders





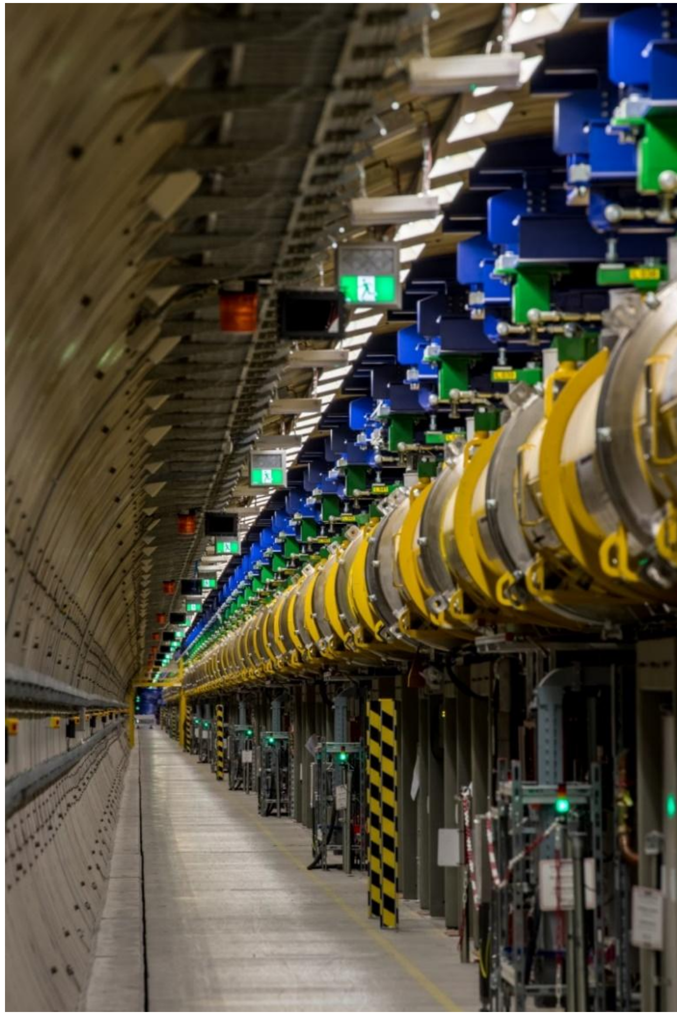
- Particle colliders collide high-energy beams together e.g. hadrons, leptons, or ions.
- Colliders led to a revolution in our physical understanding of the Universe, ultimately leading to the standard model.
  - Heavy ion colliders have discovered quark-gluon plasma and continue giving valuable data to further establish nuclear models.
  - More recently discovered “island of stability.”
- Energies are limited in part by design
  - Circular colliders limited by circumference and magnetic fields,
  - Linear colliders are limited by accelerating gradients and power.

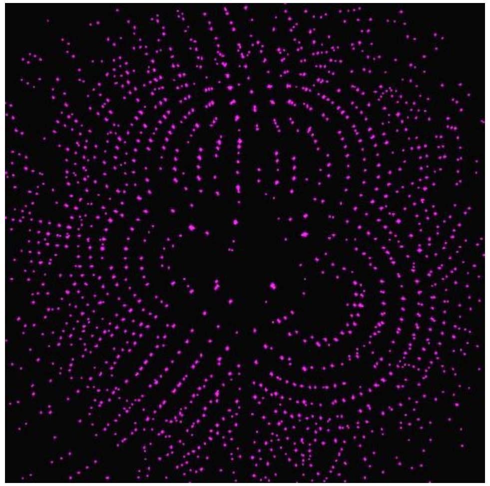


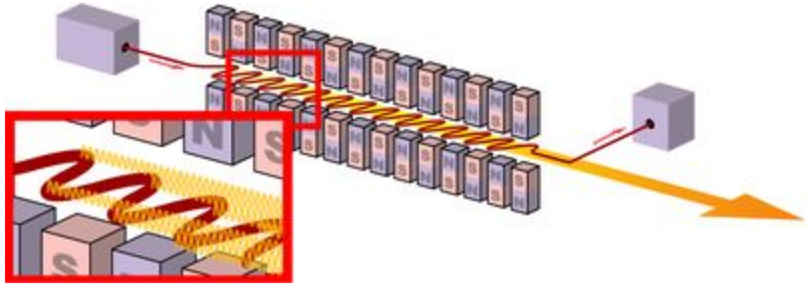
Applications

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).



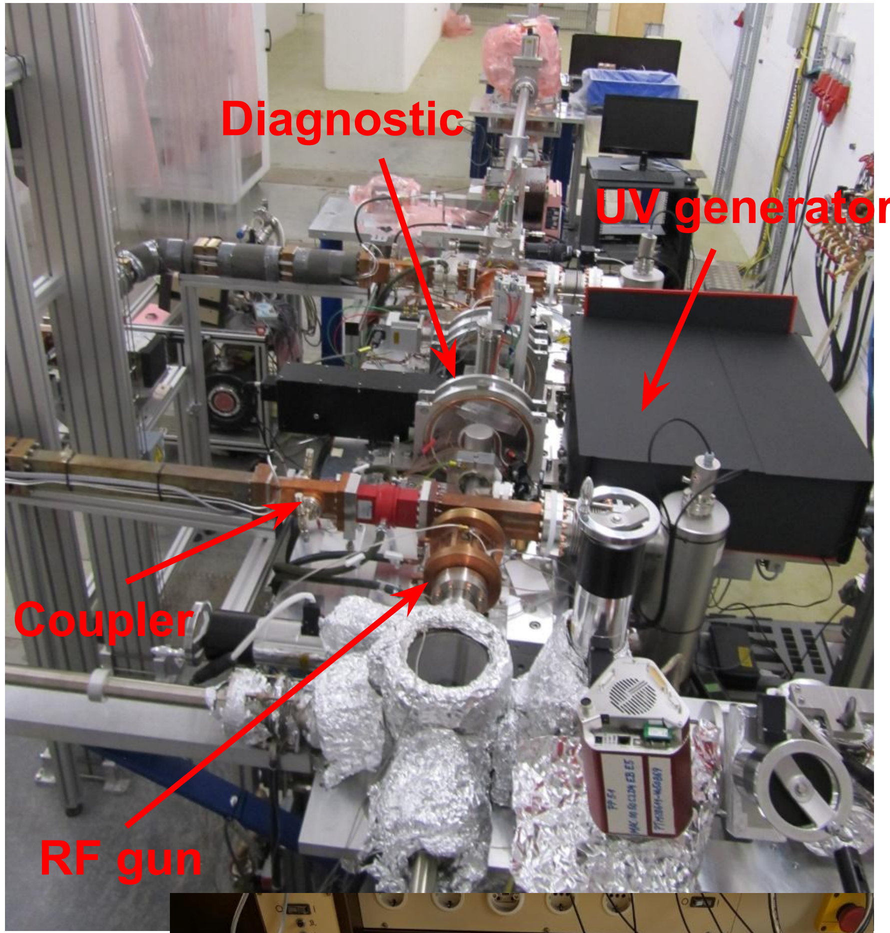


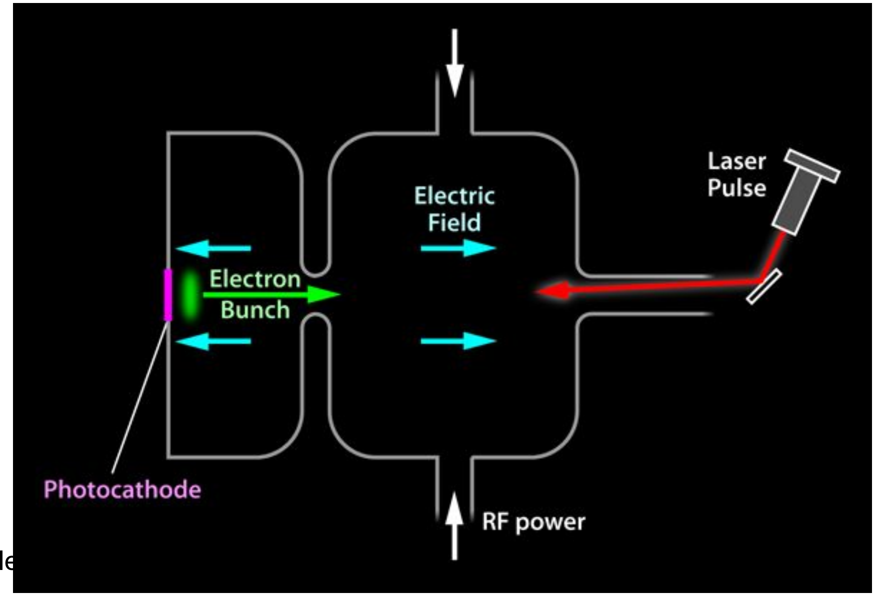


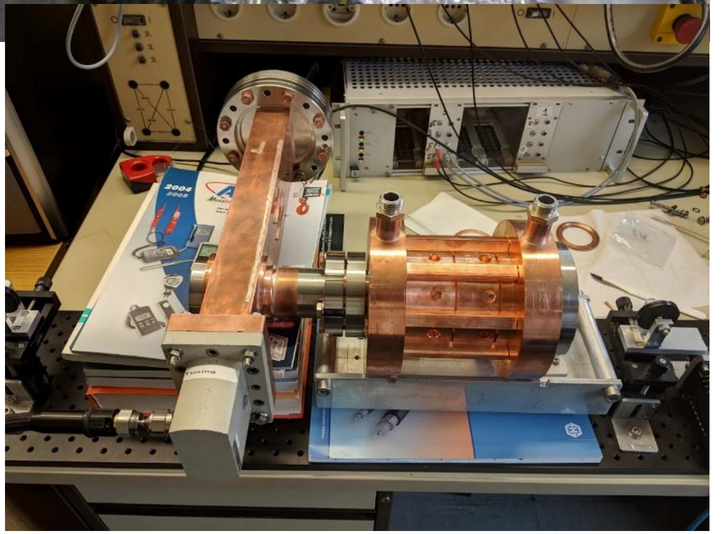
Accelerator basics

Photoelectric effect, relativistic freezeout and relativistic acceleration

- Electron bunches are generated on a photocathode from a properly timed UV laser pulse in a photoelectron gun.
- A gun is a resonant structure which supports the formation of a standing wave which is used to accelerate electron bunches.
- Radiofrequency (10 cm) wavelengths are fed through waveguides into the gun to produce 100 MV/m accelerating fields.
- These fields provide relativistic accelerating fields $\alpha = \frac{eE\lambda}{2\pi mc^2} \geq 1$



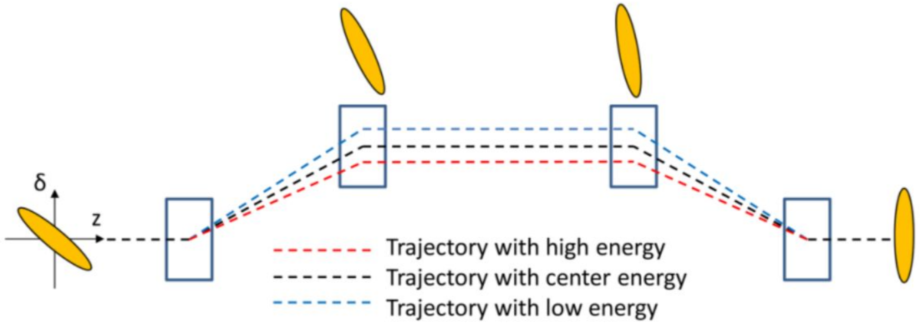




Bunch Compressors

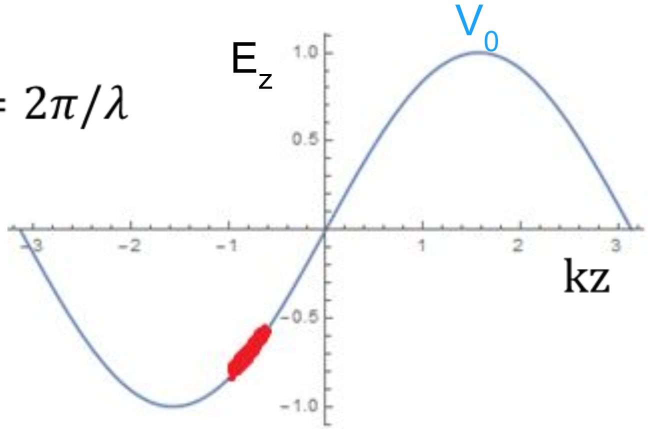
Introduction to bunch compressors

- At high-energies, the velocity differences between electrons is negligible and other means are required to compress bunches.
- Typically a bunch will be accelerated off-crest to produce a time-energy correlation, ‘chirp.’
- Subsequently a magnetic chicane with proper settings subjects the beam energy spectra to different path lengths, yielding compression.



- A first order approximation yields interesting insights to bunch compression.
- In reality, linearizing techniques are employed with 3rd harmonics or wakefield-based approaches

$k = 2\pi/\lambda$



$$E(z_0) = E_0 + eV_0\cos(kz_0 + \phi)$$

Taylor expansion yields:

$$E(z_0) = E\left(1 + p'\cdot z_0 + \frac{1}{2}p''\cdot z_0^2 + \frac{1}{6}p'''\cdot z_0^3 + \mathcal{O}(z_0^4)\right),$$

Introducing chirp: $h \equiv p' = -\frac{eV}{E}k\sin\phi,$

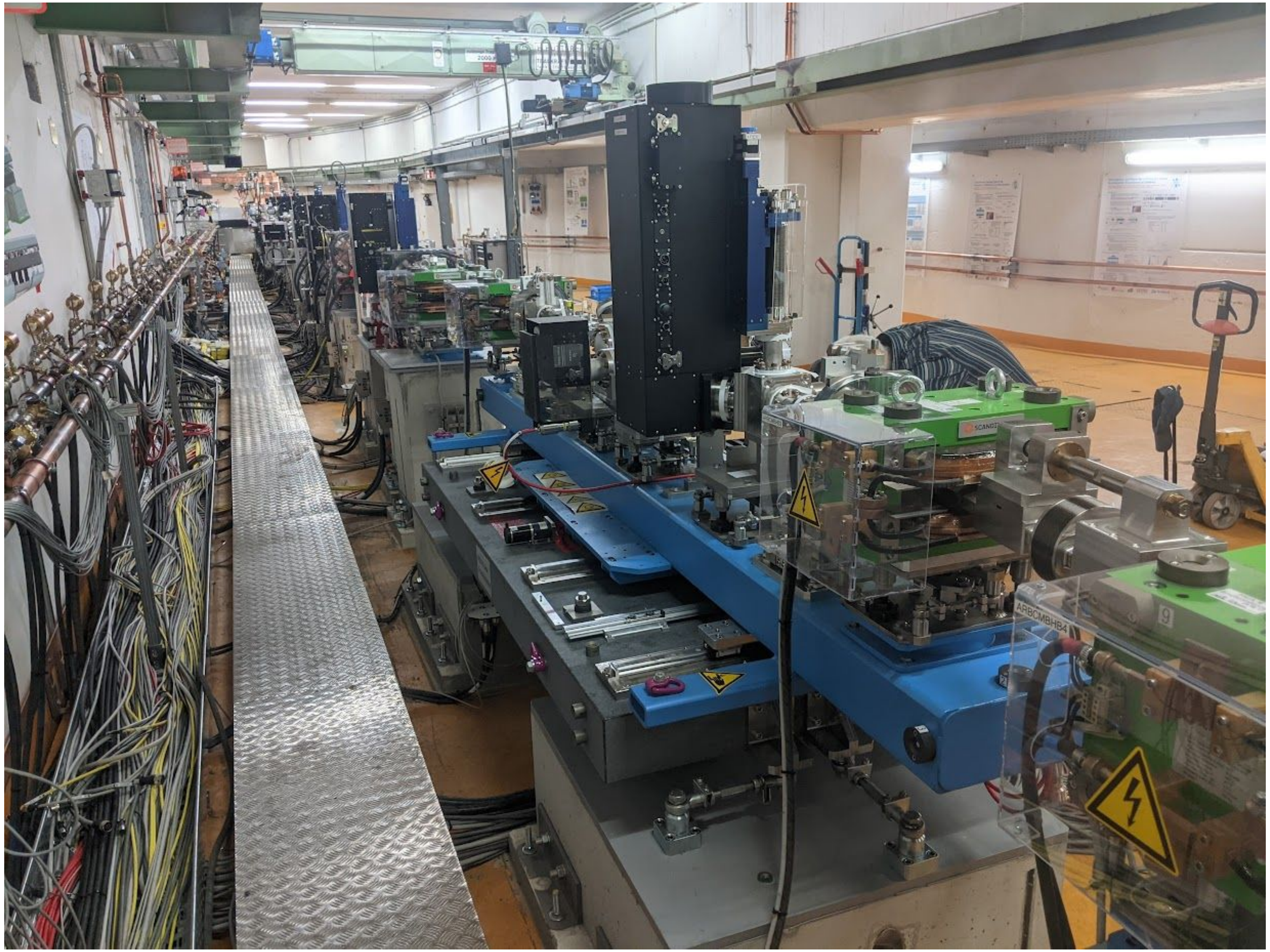
First order approximation: $\delta_i \equiv \Delta E_i / E$

$$z_1 = z_0,$$
$$\delta_1 = hz_0 + \delta_i,$$
$$z_2 = z_1 + R_{56}\delta_1 = z_0 + R_{56}(\delta_i + hz_0) = (1 + hR_{56})z_0 + R_{56}\delta_i.$$

$$\sigma_{z_2} = \sqrt{(1 + hR_{56})^2\sigma_{z_0}^2 + R_{56}^2\sigma_{\delta_i}^2},$$

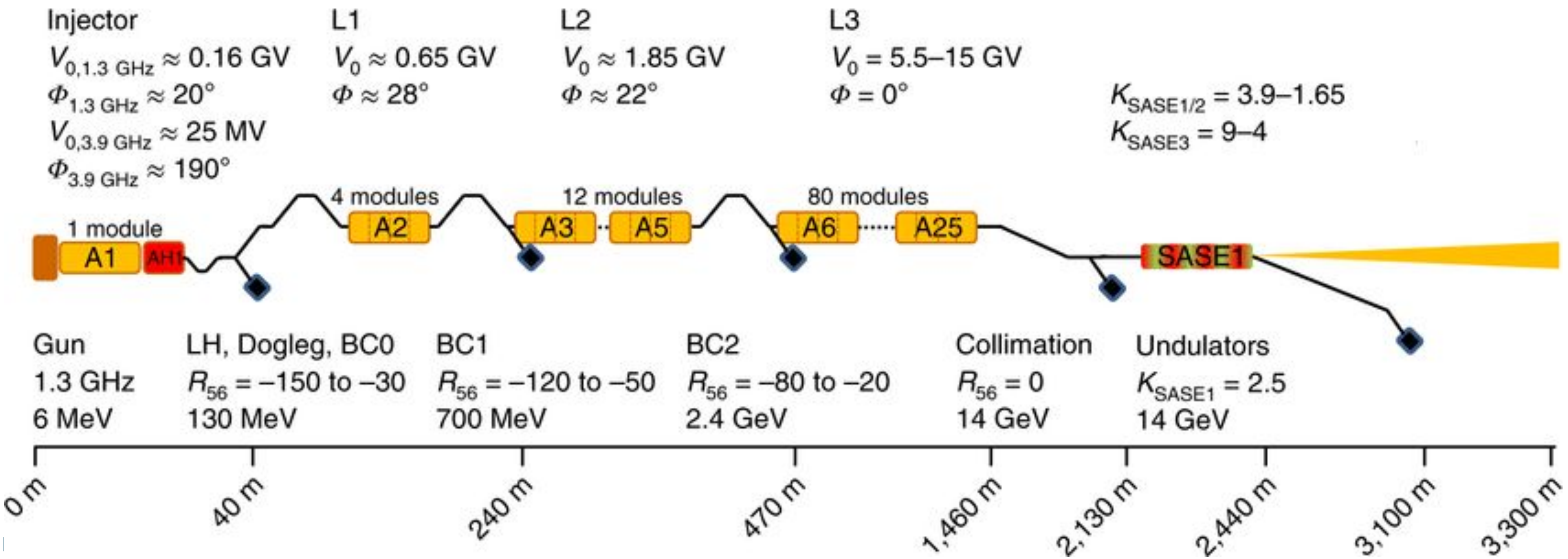
0

ARES bunch compressor now commissioning..



Layout of European XFEL

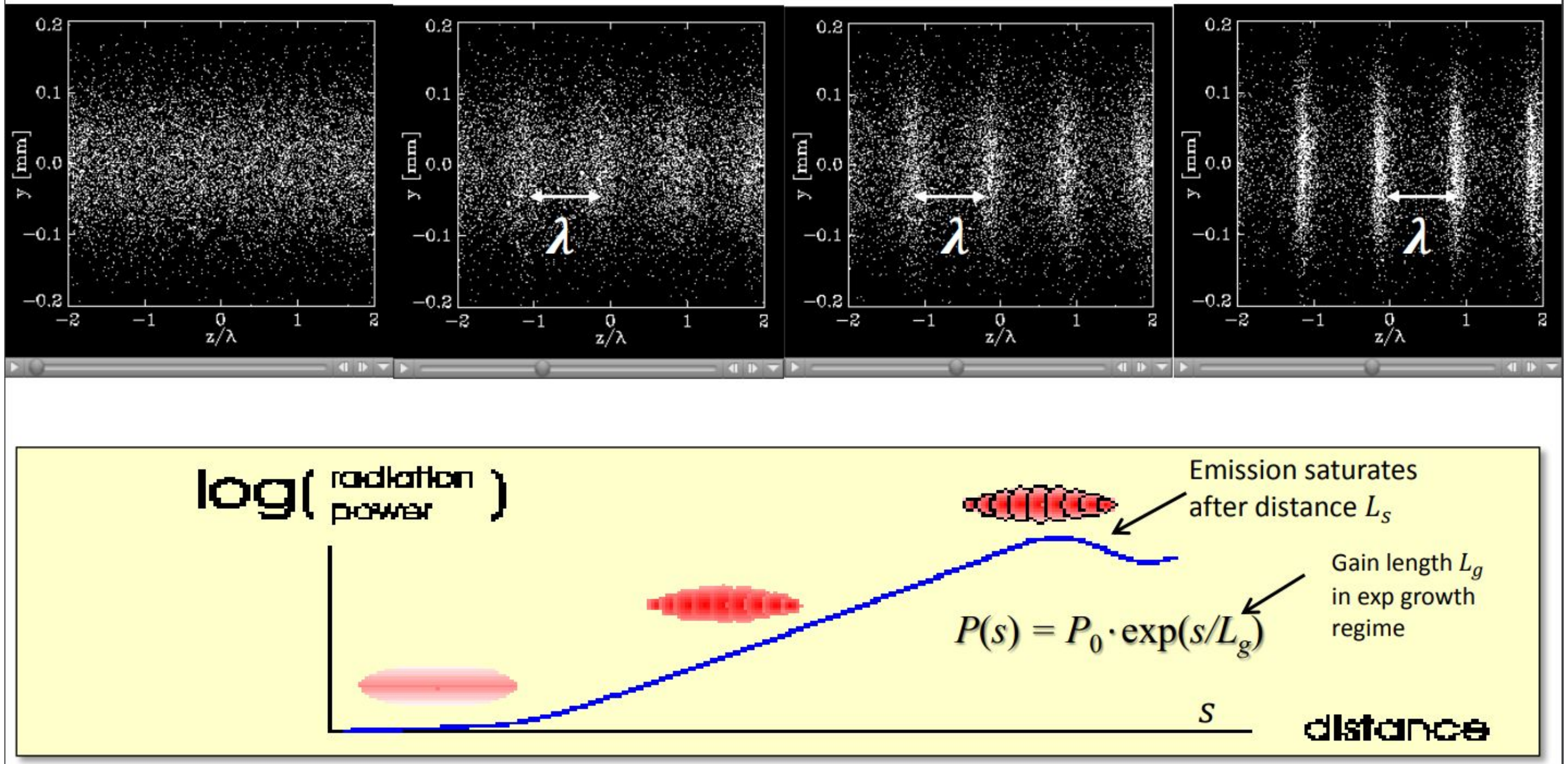
- One of the most exciting developments in accelerator physics has been the development of coherent X-ray free electron lasers
- An example of a state of the art coherent X-ray Free electron laser is shown (European XFEL)
- Several bunch compressors are used before the main linac to achieve peak currents of approximately 5 kA
- The resulting high quality bunches are fed to several undulators, in parallel, or in series, to produce mJ level X-rays.



Coherent X-ray production

In the undulators, electrons begin emitting radiation spontaneously, the produced and longitudinally localized emitted radiation acts back on the electrons, providing a new sinusoidal potential. Along the 100 m interaction distance, the electrons reorganize themselves to produce microbunches which radiate coherently.

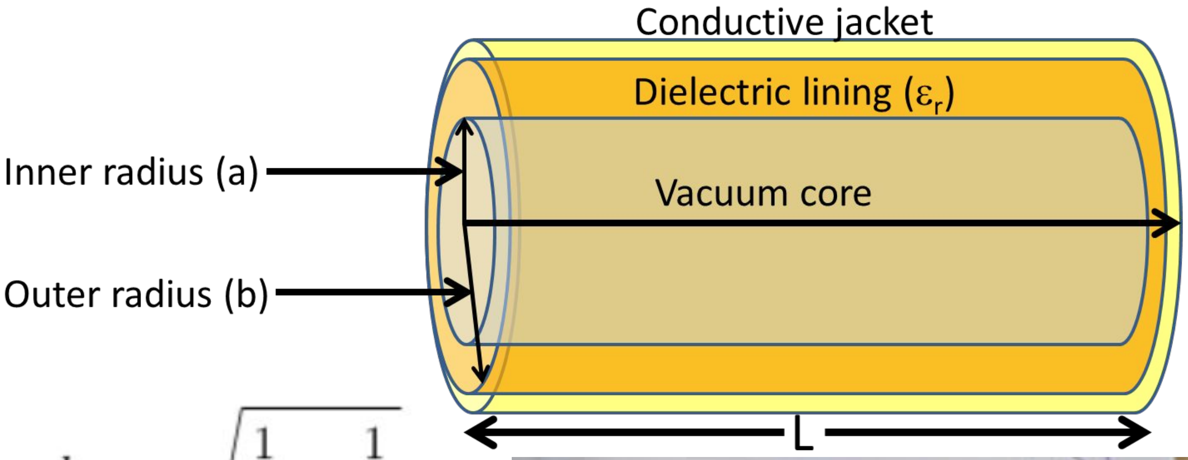
Snap shots of small portion of e-beam developing bunching along undulator line*



*Genesis simulations

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!

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

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

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

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

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

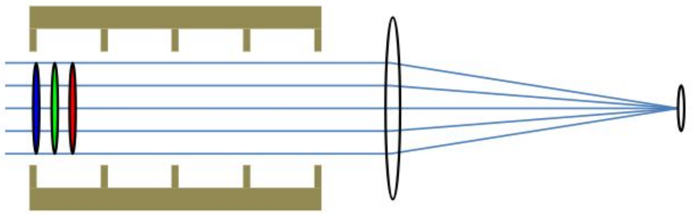
$$H_\phi = \begin{cases} \frac{-i\omega\epsilon_0}{k_1} B_1 J_0'(k_1 r) e^{i(\omega t - k_z z)} & 0 \le r < a \\ \frac{-i\omega\epsilon_r\epsilon_0}{k_2} B_2 F_{00}'(k_2 r) e^{i(\omega t - k_z z)} & a \le r \le b \end{cases}.$$

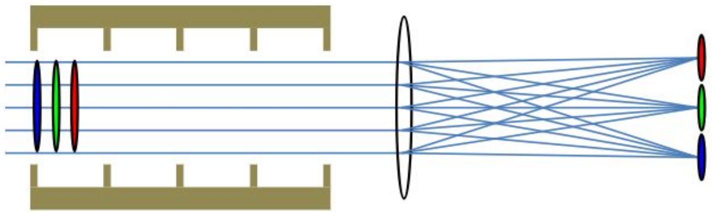
THz streaking with multicycle THz

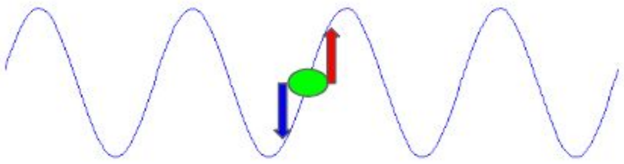
Overview of transverse deflection structures

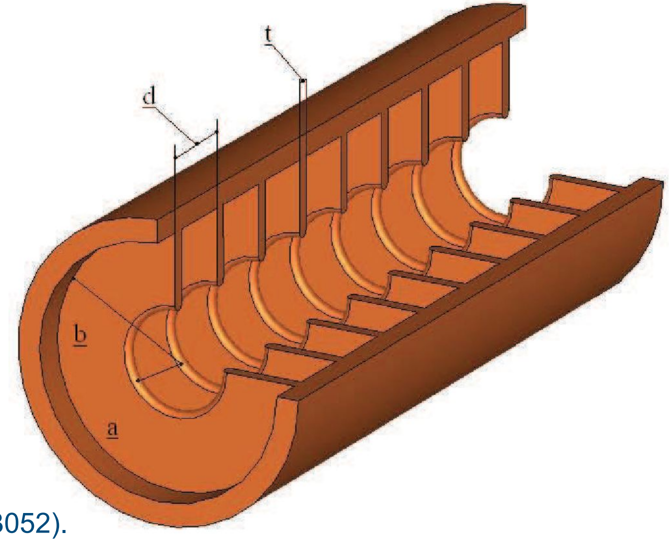
- DLWs notoriously have a large dipole mode contribution which leads to BBU.
- Can we use the THz-driven DLWs to produce a TDS?
- A TDS shears a beam transversely, mapping the temporal distribution into space
- A high resolution power 1/R requires:
  - Large integrated voltage, V
  - Short wavelength,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

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







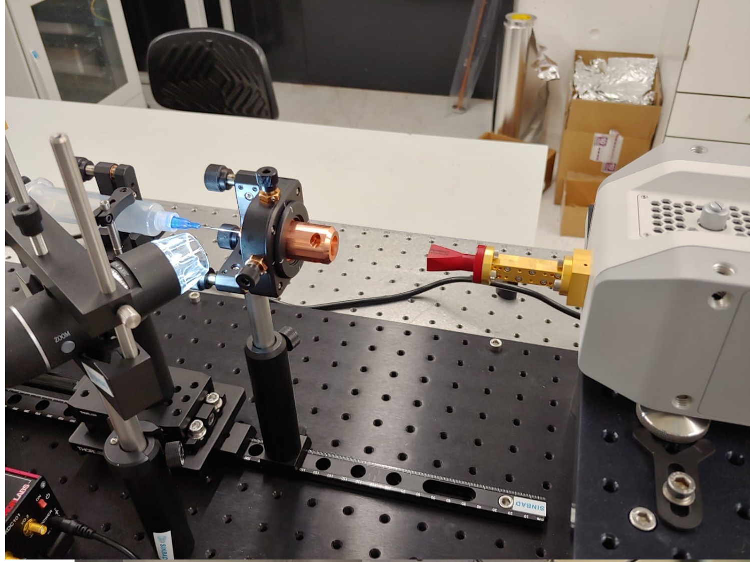


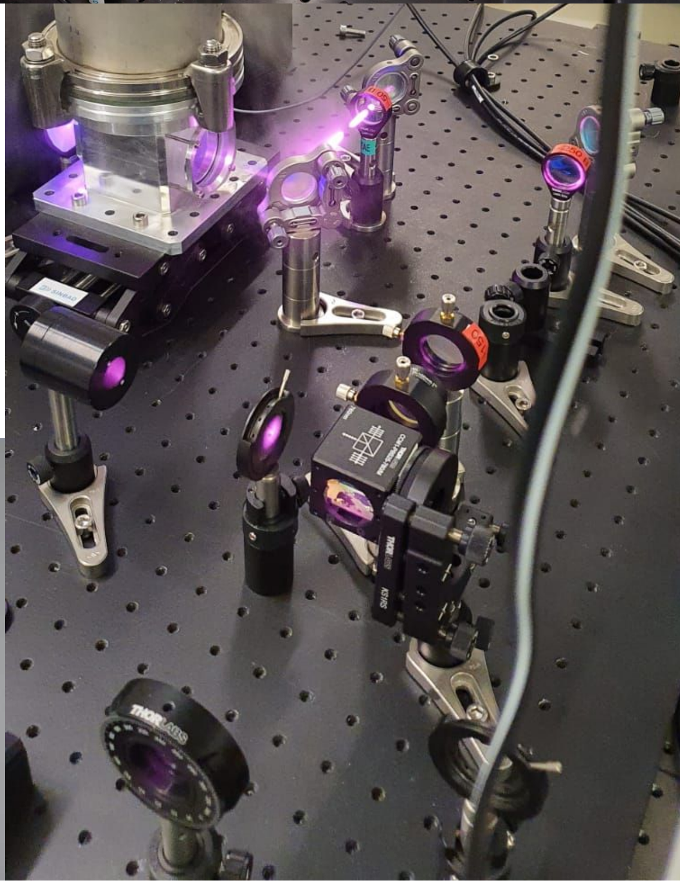
See F. Lemery, K. Floettmann, T. Vinatier, R. Assmann,
"A transverse deflection structure with dielectric-lined waveguides in the sub-THz regime," Proc. IPAC19 (MOPAB052).

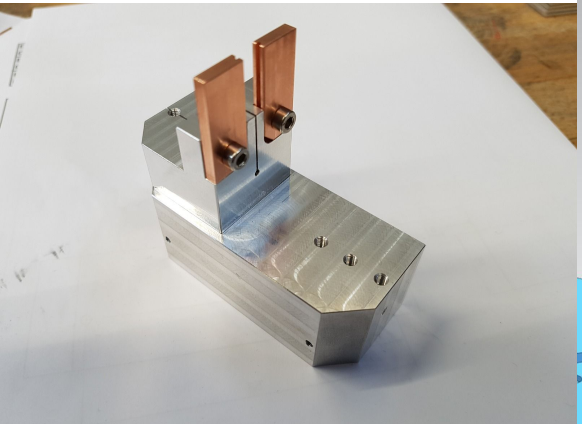
THz streaking with multicycle THz

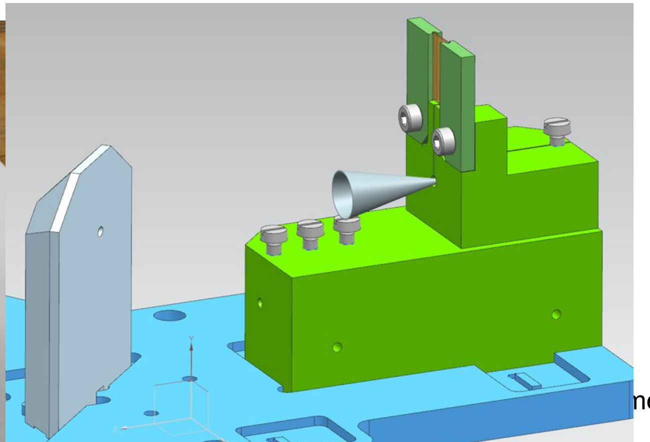
Status of experiment at REGAE

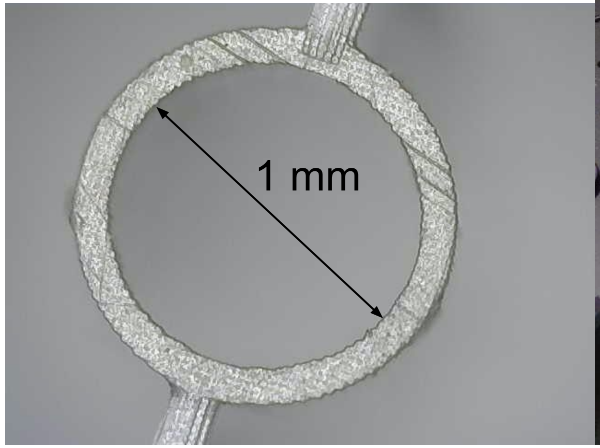
- Structures have been designed, 3D printed, coated, and tested in house.
- Currently iterating for final structure based on phase velocity measurements to reduce phase slippage in the structure. See Self-calibration technique for characterization of integrated THz waveguides M. Kellermeier, F. Lemery, 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).





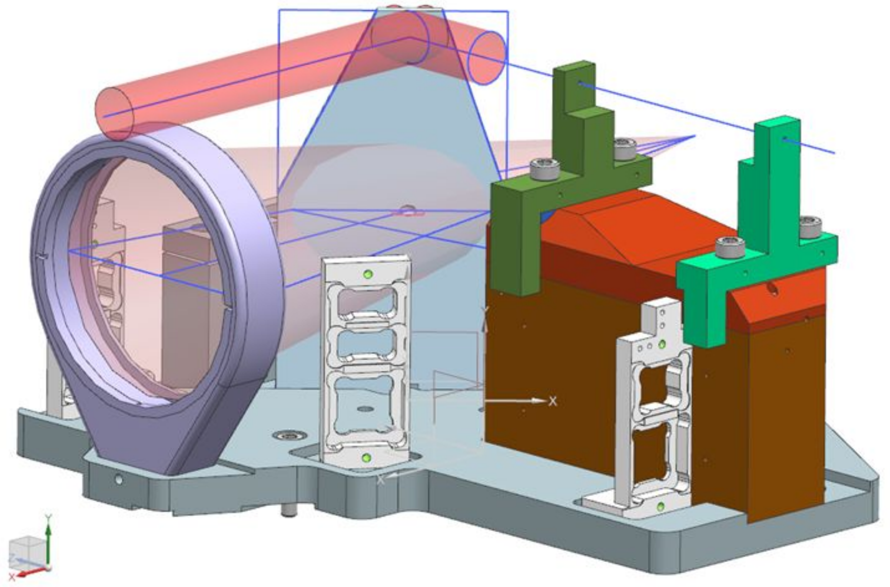


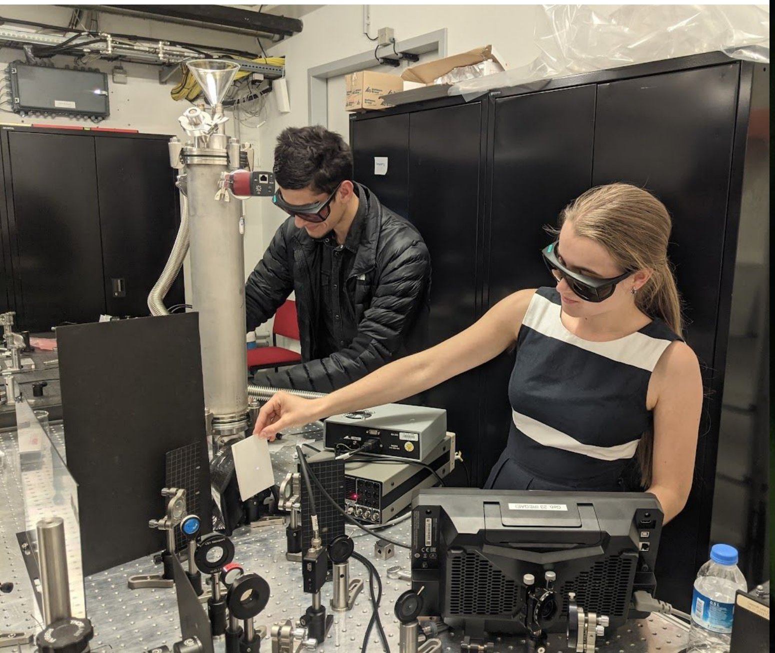


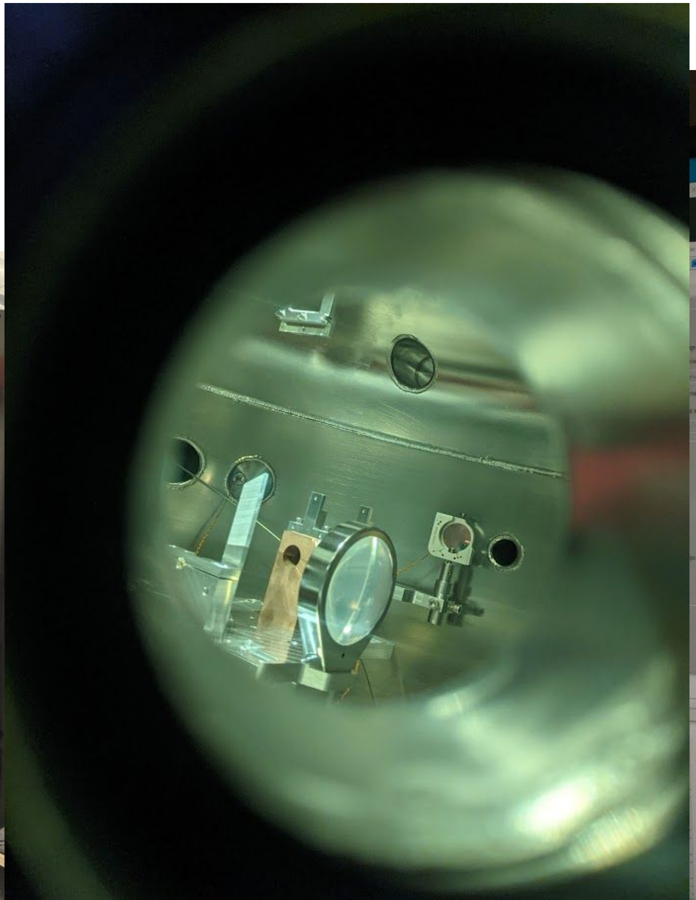


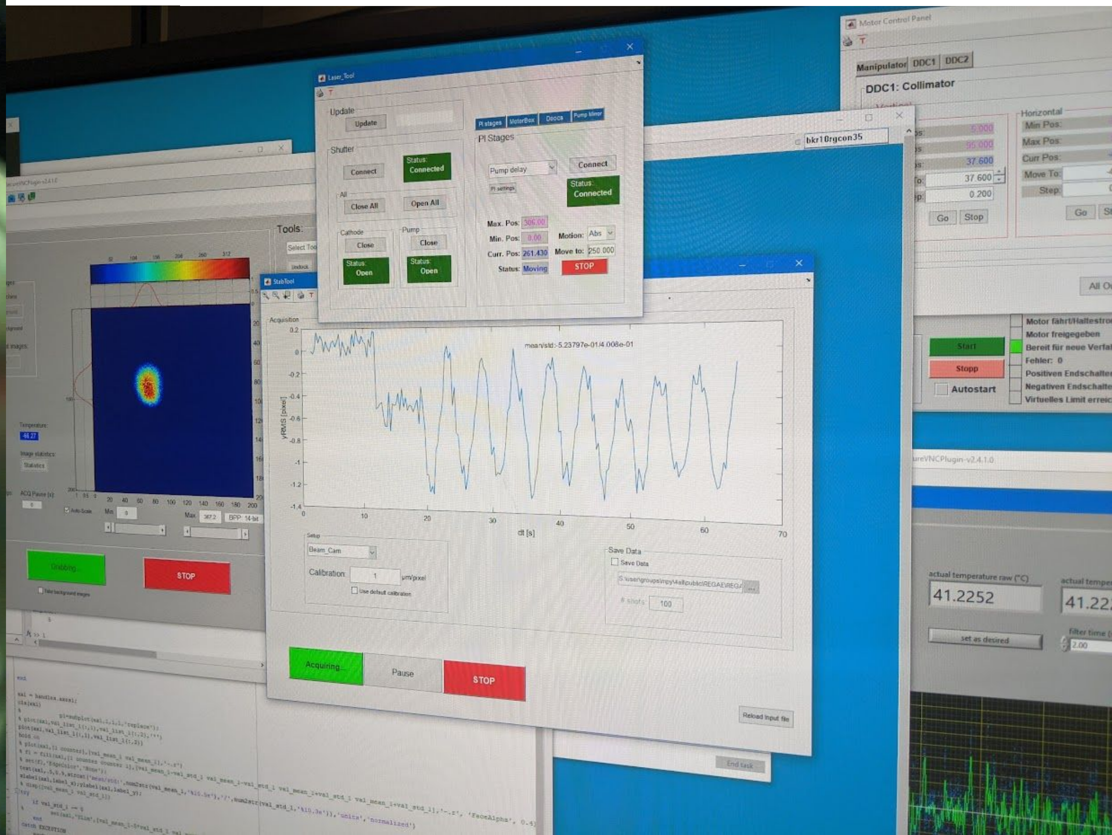
Current status of streaking experiment

- First results obtained, now improving coupling efficiency with new hardware and improving THz source.



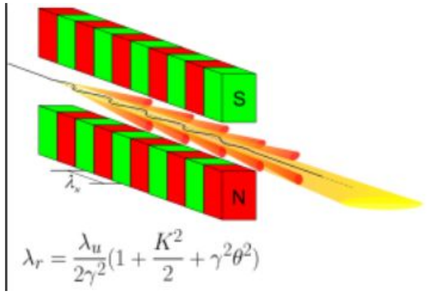


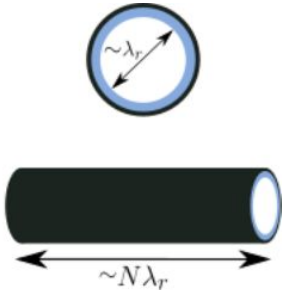




Radiation generation with charged beams

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



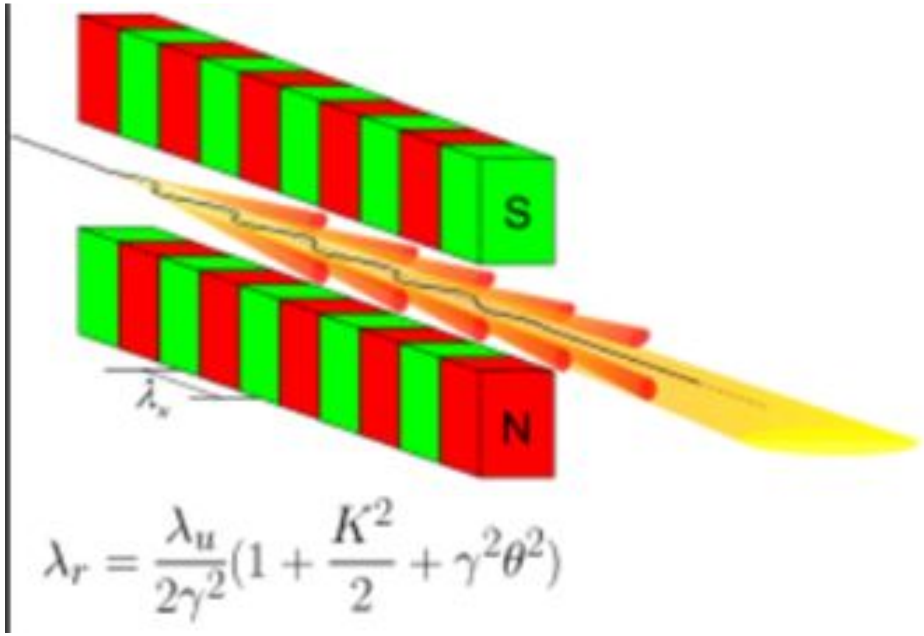


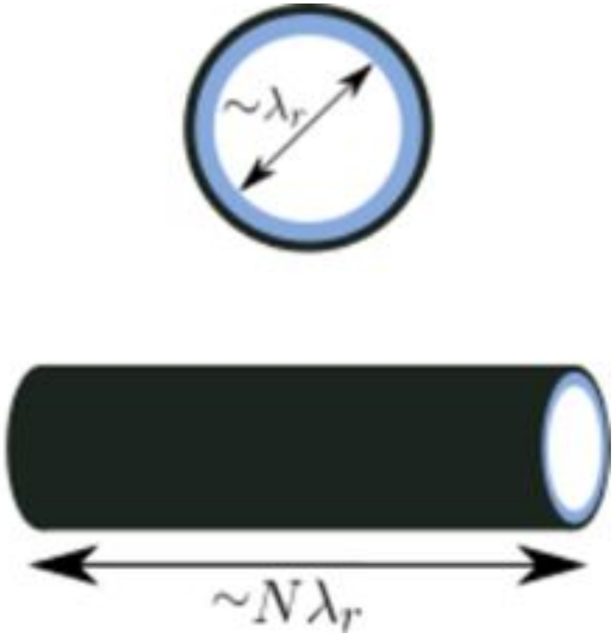
- Developed THz generation collaboration with CANDLE, Armenia
  - M. I. Ivanyan, L. V. Aslyan, K. Floettmann, F. Lemery, and V. M. Tsakanov. Wakefields in conducting waveguides with a lossy dielectric channel. Phys. Rev. Accel. Beams **23**, 041301 (2020).
  - K. Floettmann, F. Lemery, M. Dohlus, M. Marx, V. Tsakanov, M. Ivanian, “Superradiant Cherenkov-Wakefield radiation as a THz source for FEL facilities,” *Accepted Journal of Synchrotron Radiation*
- 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.
- 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.
- WE were recently awarded the *STERN* proposal, which seeks to investigate this for the European XFEL in the next three years.

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

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



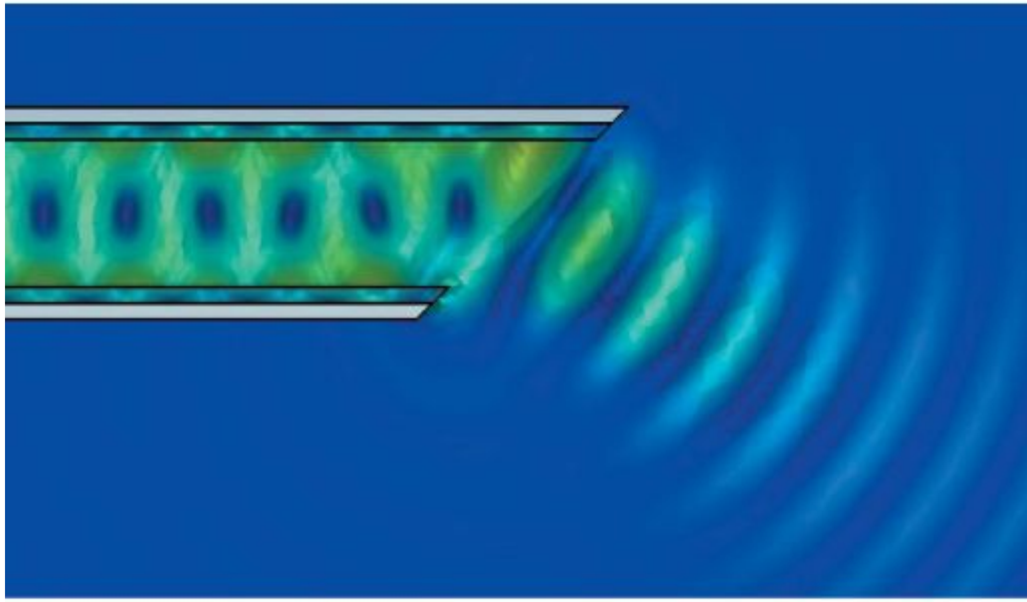


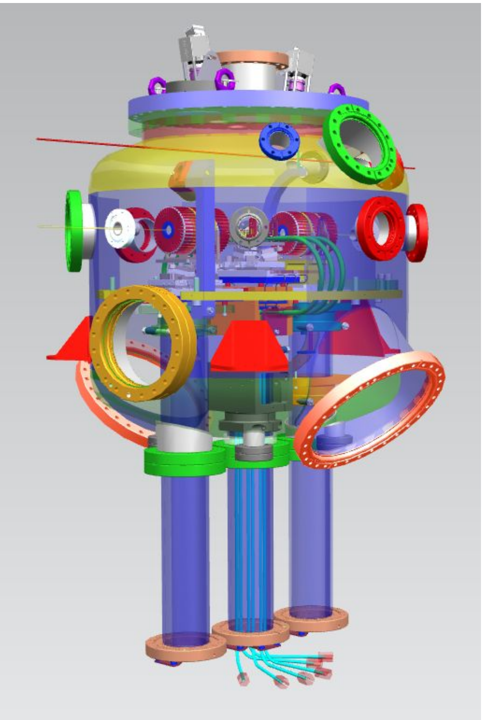
Location of experimental area

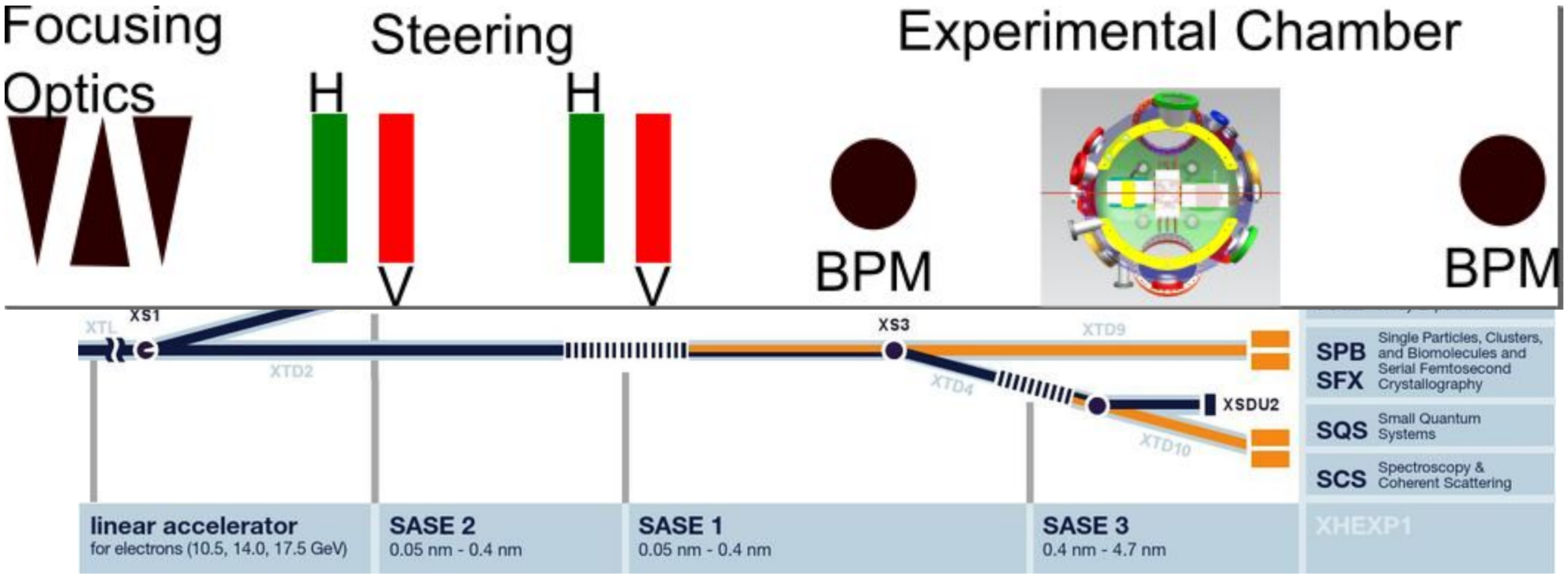
Planned for installation in 2025 at XTD5.

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

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







Happy birthday Johann

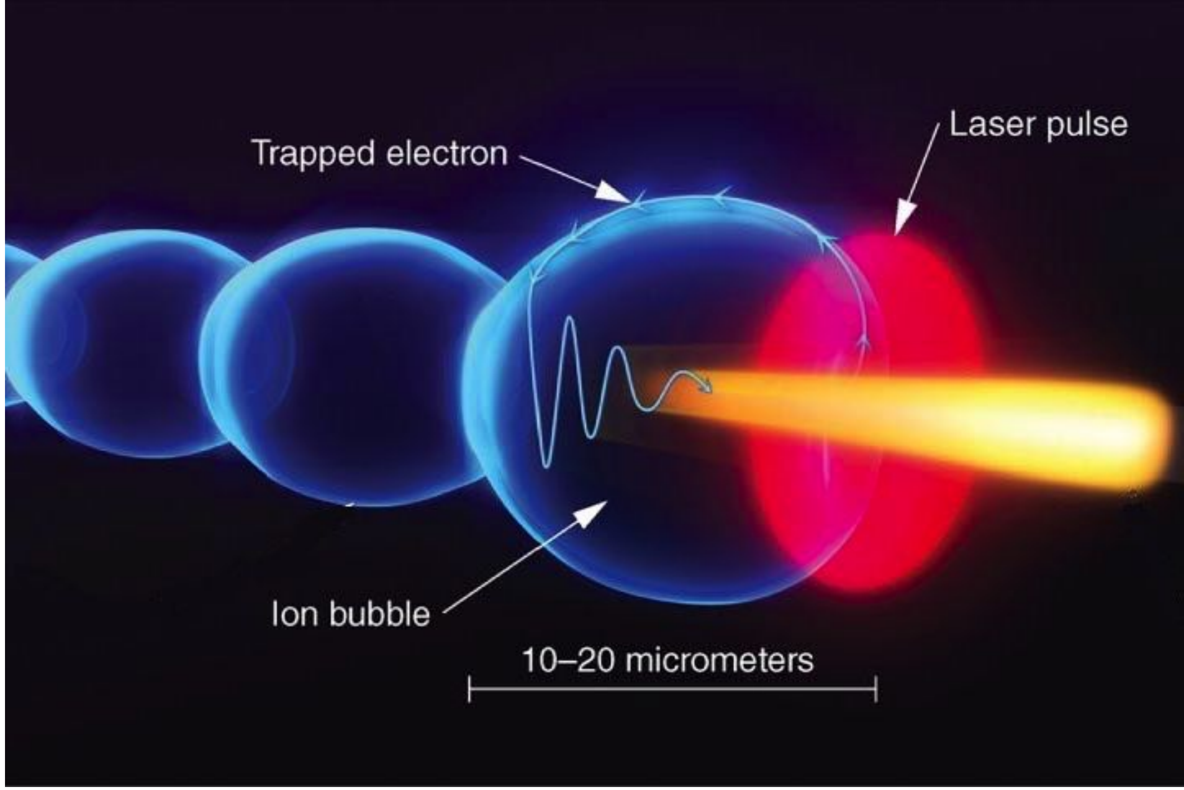
New techniques

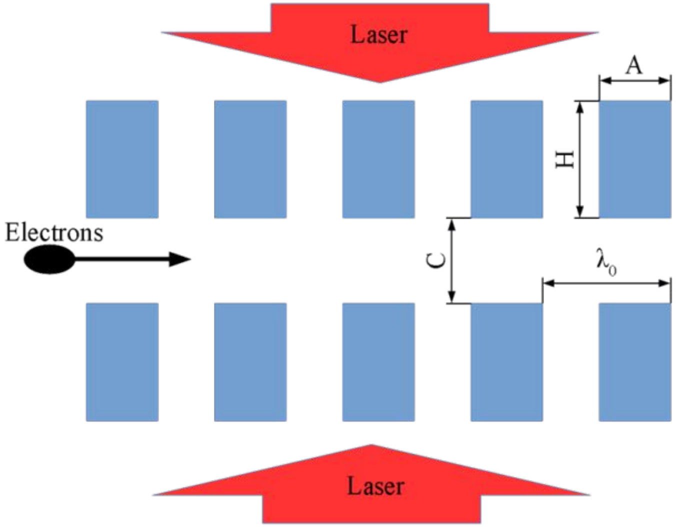
New promising techniques for acceleration

- Laser-driven plasma acceleration uses a high-power (100+ TW) laser driver to produce a very high-gradient accelerating field in a low-density gas (10^17).
  - Has demonstrated GeV beams over ~10 cm.
  - Usually suffers from poor energy spreads, repetition rates, and shot-to-shot fluctuations.

- Beam-driven acceleration uses conventional RF-based accelerators to drive large wakefields in plasmas or dielectric structures.

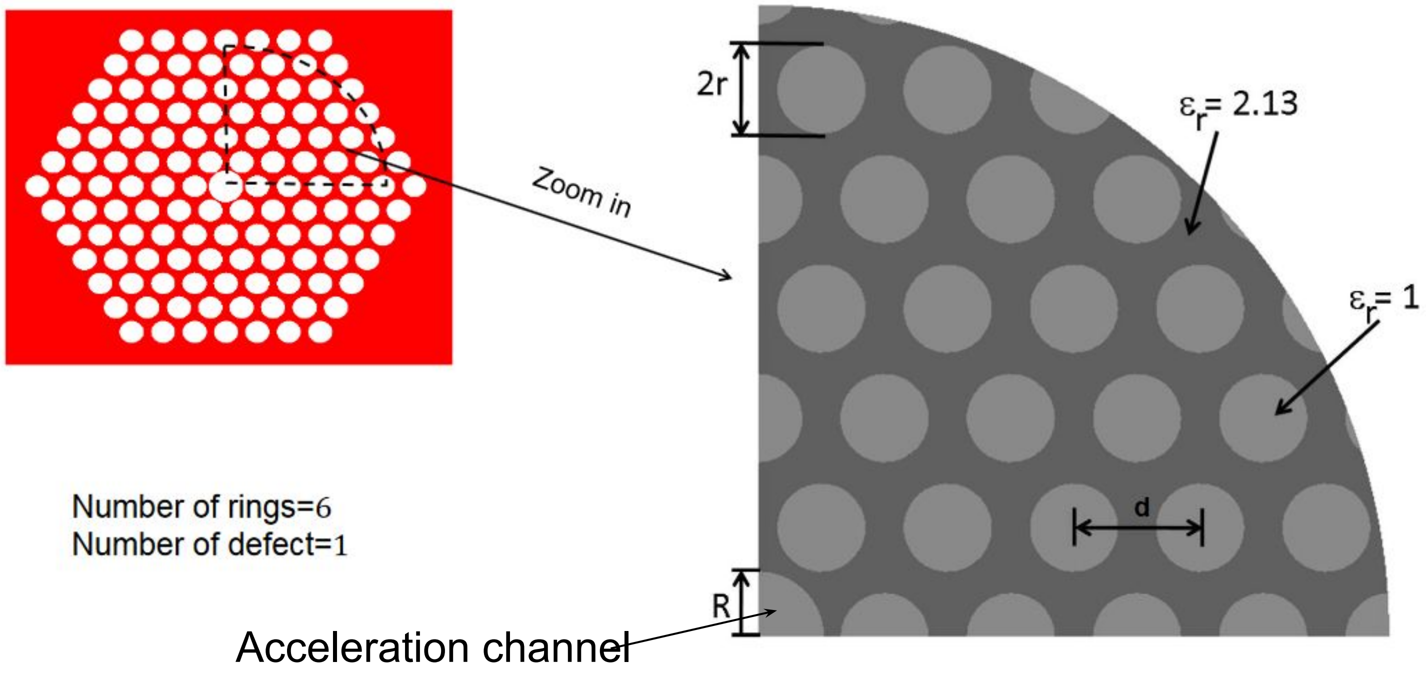
- Dielectric-laser acceleration uses lasers to accelerate particles in micron-scale dielectric structures
  - This has the advantage of requiring very small energies to support large accelerating fields.
  - The smaller charges per bunch can be overcome with repetition rate.
  - We need to develop cylindrical-symmetric DLAs

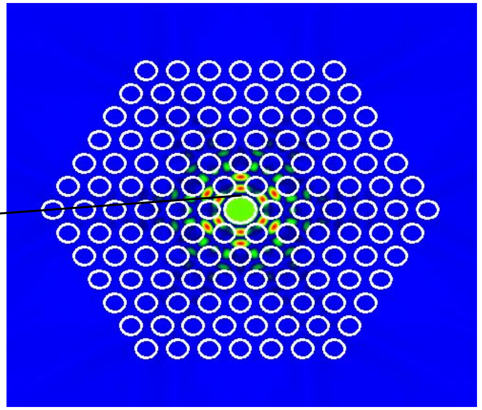


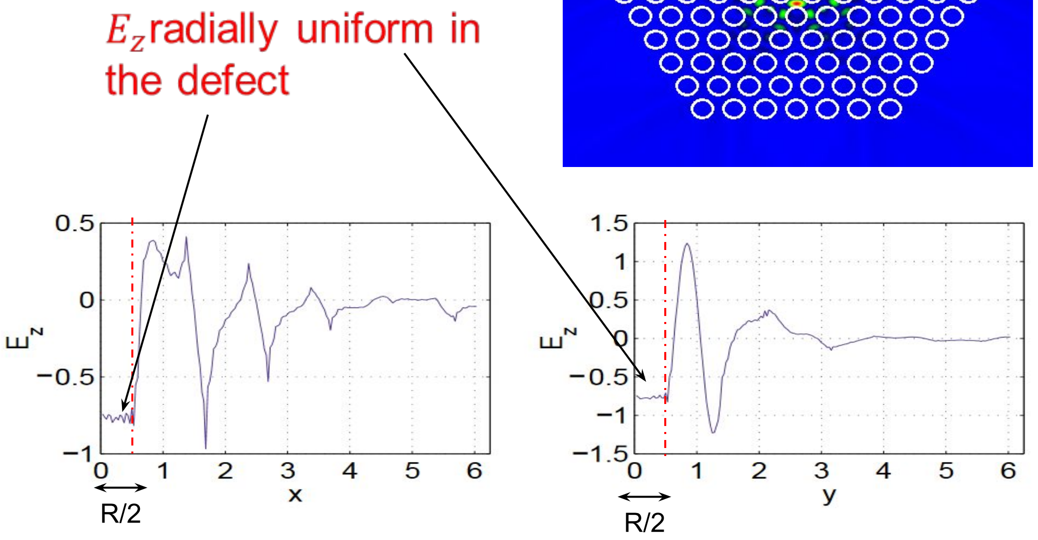


Photonic Band Gap Fiber Accelerator (PBGFA)

- Eddie Lin proposes the use of a photonic crystal fiber to support an accelerating mode (2001).
- Lin demonstrates that the mode supports uniform accelerating fields across the channel.







PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME **4**, 051301 (2001)

Photonic band gap fiber accelerator

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(Received 29 September 2000; published 31 May 2001)

There are three requirements in making a traveling wave accelerator: longitudinal electric field, synchronization, and confinement. We present and analyze a conceptually new kind of charged particle accelerator, making use of a photonic band gap lattice for field confinement near the beam axis, and employing dielectric material to produce a speed of light synchronous longitudinal electric field. An example structure design is presented. We also discuss nonlinear effect and other configurations without higher order dipole modes. Parallel scheme and fabrication are presented.

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