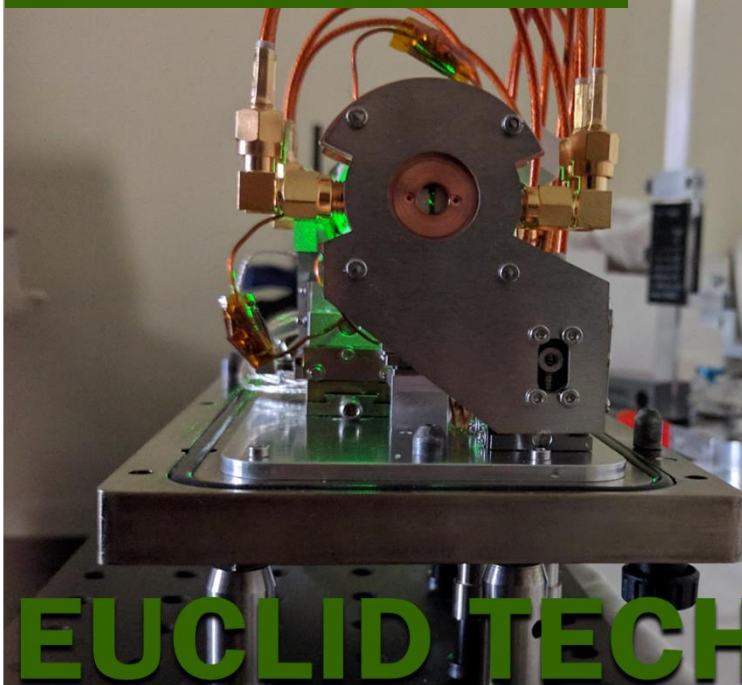


DOE SBIR/STTR Success



Electron beam modulating apparatus for producing a high-frequency, pulsed electron source for time-resolved commercial transmission electron microscopes. Device viewed from the top during the laser alignment procedure. The unit consists of a beam focusing element and a GHz buncher. All components are mounted on a vacuum compatible 3-axis translation stage

EUCLID TECHLABS

Sometimes the most notable innovations in science come from linking traditionally separate or independent knowledge. Specifically, synergies happen when mechanisms known and adopted in one scientific domain are modified to produce new concepts in a different domain. Often, such cross cutting approaches need to be encouraged because of the highly specialized fashion in which each scientific field evolves. Yet, sometimes they spur spontaneously as the result of a fortuitous encounter. Euclid TechLabs LLC (Euclid for short) is an R&D small business specializing in the design and development of particle accelerators and their components for high energy and nuclear physics applications.

FACTS

PHASE III SUCCESS

Euclid's product sales have reached \$ 1.6 M in 2016-2017. Phase III achievements include a \$680k contract from NIST in collaboration with BNL and JEOL

IMPACT

Euclid's electromagnetic-mechanical buncher makes it possible for an electron microscope to reach the ultimate space-time resolution of 10^{-20} to 10^{-23} m·s necessary to probe ionic, charge, and spin transport in advanced energy materials.

DOE PROGRAMS

Nuclear Physics (NP), Basic Energy Sciences (BES), High Energy Physics (HEP).

Euclid has been a pioneer in the development of dielectric wakefield accelerators, and after extending its expertise to radiofrequency (RF) accelerators, Euclid has provided U.S. National Laboratories, Universities and Industry with major innovative instruments and technologies over the years. However, it was the encounter of Alexei Kanareykin, Euclid CEO and founder with colleagues expert in transmission electron microscopy (S. Baryshev) and radio frequency (RF) cavity design (C. Jing) that launched Euclid's most significant commercialization achievement to date.

Euclid's team realized that they could contribute their 20-year expertise in beam physics to solve a crucial limitation in electron microscopy and advance this already powerful technique to the forefront of *in-situ* characterization of nano- and atomic-scale processes. Transmission electron microscopy (TEM) is the gold standard for high spatial resolution characterization of advanced materials, allowing for atom-resolved imaging and spectroscopy, which are not possible with x-ray or laser microscopes. However, because the electron beam produced in the TEM gun is continuous (dc), conventional TEM is not able to temporally resolve dynamic events associated for example with ion and electron transport. The possibility offered by Euclid to modulate the electron beam in a series of femtosecond short pulses with a repetition rate in the GHz range opens up a new frontier of non-equilibrium materials science.

Thanks to spectroscopy and diffraction methods, TEM can image not only the atomic structure but also the electronic structure of materials. Considering that typical velocities of electrons in solids and atoms/ions propagation are in the range of nanometer/femtosecond and nanometer/picosecond, respectively, ultrafast microscopes with the ultimate space-time resolution of 10^{-20} to 10^{-23} m · s will be able to probe ionic, charge, and spin transport at interfaces and heterostructures, which is key to understand the physics and chemistry of batteries, catalysis, fuel cells, emerging magnetic information storage devices, and novel materials synthesis. For example, in some memristors, reversible conducting channels a single atom wide form as a result of the motion of ions, and they have yet to be resolved¹. Ultrafast electron microscopy can also allow for direct visualization of nanoscale heat transport and phonon scattering mechanisms, which are the basis for tailoring heat dissipation in modern microprocessor computer chips².

Currently, the only ultrafast TEMs available use a laser to induce intermittent electron emission from a photocathode. This approach is not ideal because it involves a complete alteration of the electron gun with risk of heating damage from the laser, and most importantly, because lasers cannot achieve the GHz sampling rates which are so important for capturing nanosecond physical processes and enhancing the signal-to-noise ratio, thereby producing sharp, fast successions of images and spectra. Euclid's innovative idea is to use the RF cavity resonator technology to manipulate the TEM electron beam. In this way, the physics and methods widely adopted in electron beam accelerators are employed to produce a fundamentally different stroboscopic instrument, which can be built on any TEM platform, because the electron emission process is unchanged. Euclid's patented technique consists of a series of magnetic quadrupoles and stripline resonators in place of deflecting cavities to achieve ultra-broad tunability. This apparatus modulates and chops the incoming dc electron beam and converts it into pico- and sub-pico-second (100 fs to 10 ps) electron pulses with repetition rates larger than 1 GHz. The device is named electromagnetic-mechanical buncher or electron buncher for short. The resulting pulses do not experience phase-space degradation compared to the incoming dc beam, requiring no change in the complex electron optics that makes up the core of a TEM.

Although the principle of beam modulation is widely established in accelerator beam physics, fundamental changes to cavity design, materials and processes needed to be applied by Euclid's team to manipulate a TEM beam. This is because the TEM electron beam is much less energetic than the electron beams produced in accelerators. The energy difference gives rise to technical challenges in focusing and manipulating the beam, and especially in avoiding buildup of charge caused by the beam interaction with the insulating cavity.

The knowledge required to develop Euclid's electron buncher technology for the next generation ultrafast TEMs is strongly linked to technologies and products that Euclid developed through previous DOE SBIR grants, including the design and fabrication of turnkey accelerator systems and ultra-compact low energy accelerators, and a variety of accelerator components, from RF windows to low loss ceramic and ferroelectric materials. Many of these products have reached the market and Euclid has reported \$1.6M in sales for the period 2016-2017. Some Phase II projects have recently reached Phase III. This is the case of a DOE Nuclear Physics (NP) Phase II SBIR project completed in January 2018, which has just received a Phase III contract for accelerator components testing at CERN, the European Organization for Nuclear Research. The project involves development of nonlinear ferroelectric microwave components for tuning RF cavities through a bias voltage. The Phase III project will test a 400 MHz tuner developed in Phase II on a CERN superconducting RF cavity and the second stage will involve a CERN order for the new 800 MHz tuner based on the same technology.

The ultrafast TEM project is presently funded by a Phase II SBIR grant from the Basic Energy Science (BES) Program in DOE, Office of Science that started in 2016—the Phase I of the same project was awarded in 2015. Although the SBIR grant is ongoing, Euclid has already received a Phase III contract of \$680,000 from the National Institute of Standards and Technology (NIST), working with June W. Lau, Staff Physicist, and Eric K. Lin, Director of the Material Measurement Laboratory. The contract comes with a contributing share from Brookhaven National Laboratory (BNL) and its objective is to demonstrate the successful implementation of the electron buncher in a commercial JEOL TEM and to build a fully functional ultrafast time-resolved TEM with the SBIR proposal's specs. At the same time, through a collaboration agreement, the world leading manufacturer of TEMs, JEOL has provided Euclid access to its laboratory facility in Peabody, MA, which is staffed with engineers who will be working on Euclid's prototype. Successful execution of the project will lead to more close collaboration between Euclid and JEOL. The next Euclid's stroboscopic TEM installation will be at BNL, where Euclid maintains a strong collaboration with the Electron Microscopy and Nanostructure Group led by Professor Yimei Zhu, who spearheaded and currently supervises this project.

In total, Euclid has achieved returns of \$2M on the SBIR investment that funded the core technology associated with electron beam manipulation, advanced materials and related technologies. Part of this return comes from sales and part from non-SBIR contracts with the DOE, the Department of Defense (DOD) and Universities.

Euclid's recent commercialization outcomes are the result of a radical shift in Dr. Kanareykin's approach towards SBIR grants and commercialization in general, which happened in 2014. Euclid started as a spinoff company of Argonne Wakefield Accelerator (AWA) group at Argonne National Laboratory (ANL) in 2003, and until 2014 it was funded exclusively by the DOE SBIR Program and in particular by the High Energy Physics (HEP) Program within the DOE, Office of Science, which was Euclid's only customer. During these years, Euclid developed technologies and devices essential for the future electron-positron

International Linear Collider (ILC) and did not consider pursuing projects that could lead to a wider market with customers other than the DOE National Laboratories. Euclid approach changed in conjunction with a stronger emphasis on commercialization requested by Congress and implemented by the DOE SBIR/STTR Office. New grant requirements designed to foster a business-like mentality induced Dr. Kanareykin to change his perspective and pursue an outcome-oriented strategy. “Since then,” Dr. Kanareykin explains, “I look at any experimental physics method or device in very different terms, asking myself how they can be linked to a marketable product.” Since 2014, as part of its commercialization strategy, Euclid has begun expanding its sales to European and Chinese high energy physics markets and its returns have begun matching the total SBIR investment received per year, showing a pronounced upturn for 2018.

Euclid is also committed to protect its intellectual property. Up to date, Euclid has been granted 8 patents, and 7 additional patent applications are currently pending. Several of these patents and patent applications are related to ceramic material technology. Euclid currently employs 18 people among its research, engineering, and administrative staff, including 14 PhDs, and regularly hosts a group of visiting researchers and consultants.

Written By Claudia Cantoni, Commercialization Program Manager, DOE SBIR/STTR, March 2018.

¹ Report of the Basic Energy Sciences Workshop on Future of Electron Scattering and Diffraction (2014)

² Yimei Zhu & Hermann Dürr, “The future of electron microscopy” *Physics Today* 68, 4, 32 (2015).