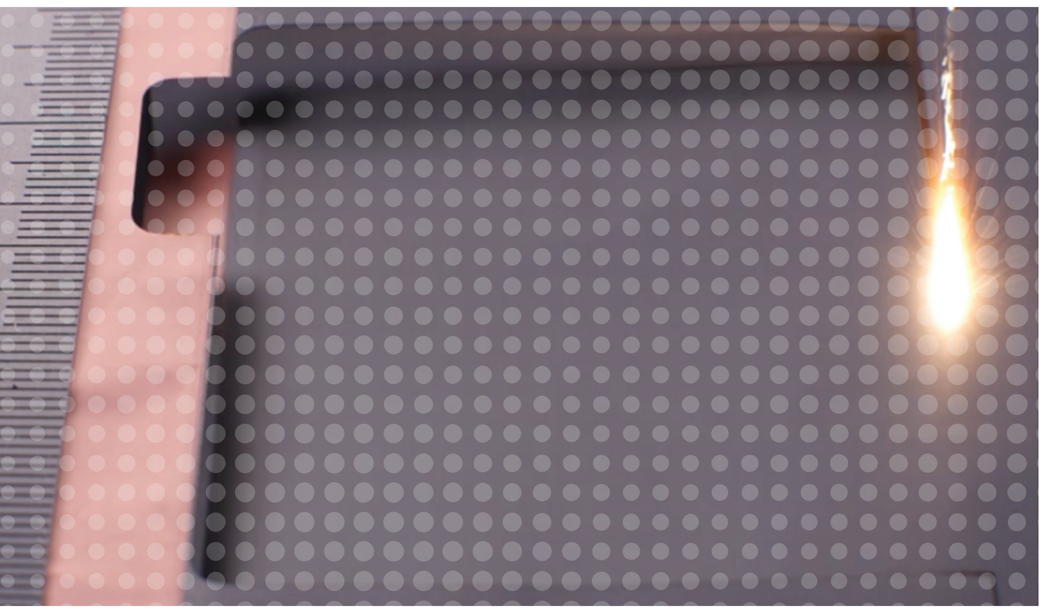
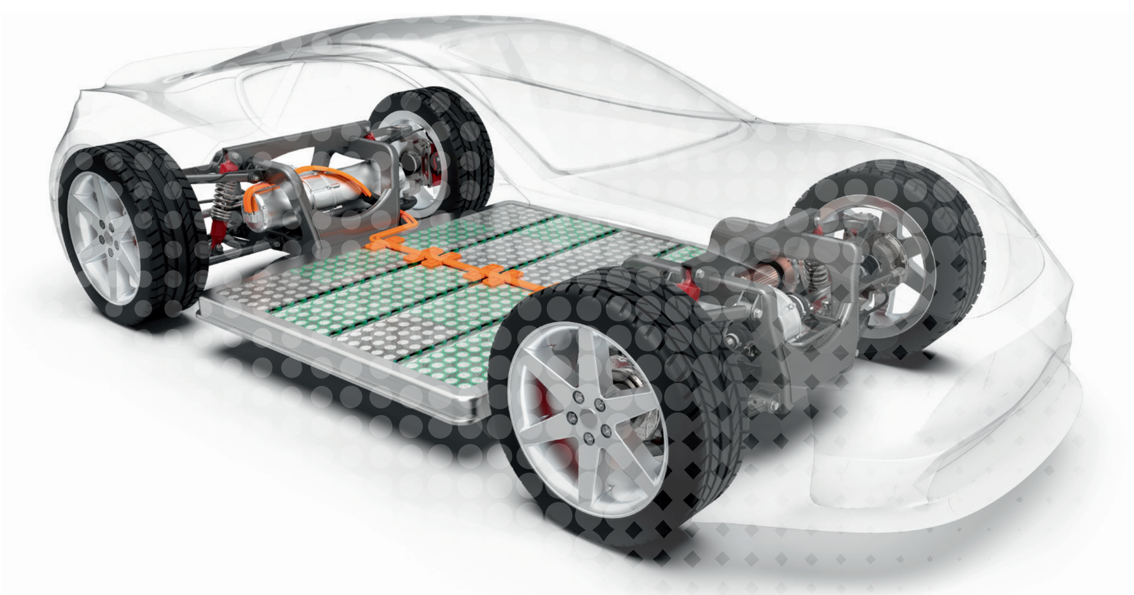
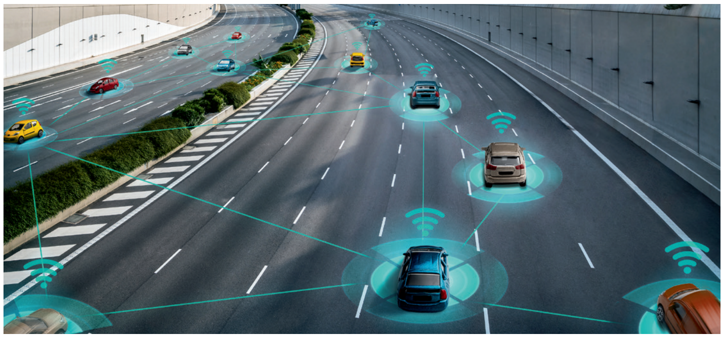
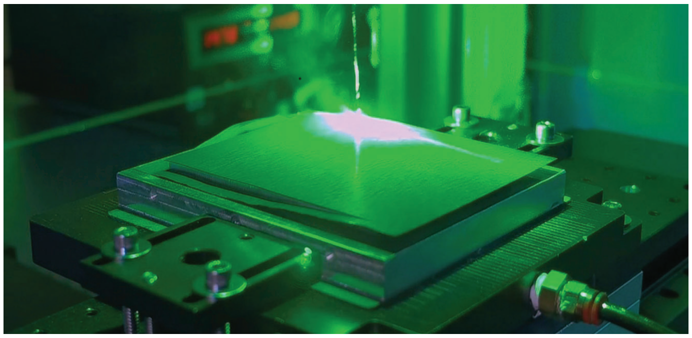
TRANSFORMING LITHIUM-ION BATTERY MANUFACTURING









POWERING A CLEANER, ELECTRIFIED WORLD

Two distinct, yet connected, worldwide societal transformations have accelerated in the new millennium. One is the rapid rise in the ability—and desire—to live in a mobile world with not only electronic personal devices like smart phones, watches and other wearables, but also with various equipment and instruments such as power tools and medical devices. The other is the quest for cleaner energy with the power and scale of a global consciousness, which is especially evident with the growing use of electric vehicles (EVs) and renewable energy sources.

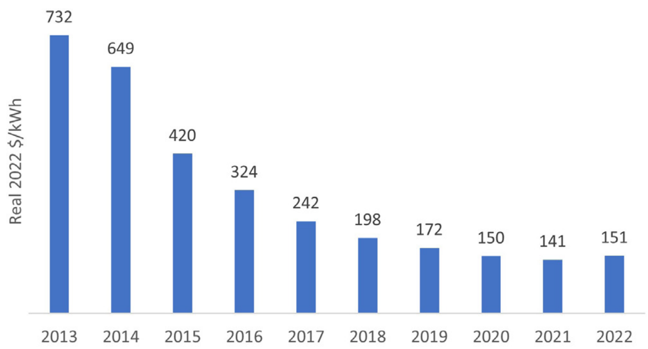
All of these technologies require batteries. Without batteries, mobile devices would not truly be mobile. Vehicles can now be propelled by electromotive force instead of gasoline combustion because of batteries. And due to the intermittent nature of certain renewable energy sources—such as solar and wind—batteries can store energy during a surplus of renewable energy to help meet periods of peak electricity demand.

With their ability to provide large energy capacities in small, lightweight packages, lithium-ion (Li-ion) batteries have become a leading, and critical, option to power a cleaner, electrified world.

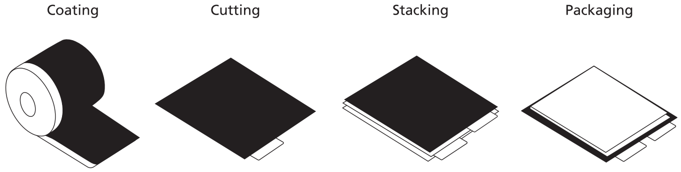
Li-ion Battery Manufacturing Challenges

When Li-ion batteries were first introduced some 30 years ago, they were very expensive. Even just ten years ago, the cost per kilowatt-hour (kWh) of a Li-ion battery was several hundred US dollars. But since then, prices have fallen dramatically. Many believe that a major breakthrough in widespread adoption will occur when prices fall below \$100/kWh, as this is the price point where the cost of EVs will start to match that of traditional internal combustion engine cars. Industry is on the path to reaching \$100/kWh—despite a price increase in 2022 that was likely caused by rising costs of raw materials and components and overall inflation—but there is still much work to do to reach that goal. Looking beyond this milestone, some even foresee levels down to \$60/kWh.

Average Li-ion battery price

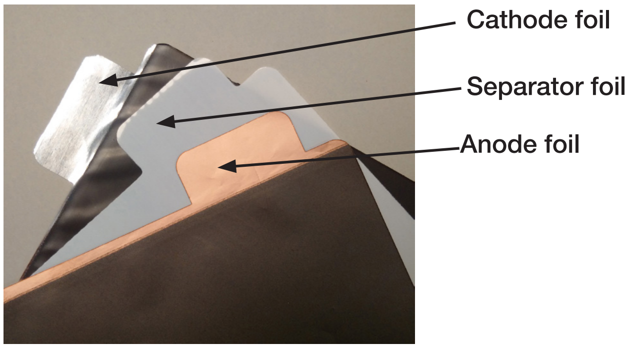


Bloomberg NEF



Typical key steps in Li-ion-cell manufacturing process

In a typical Li-ion cell manufacturing process, the electrode foils start out as rolled, coated layers that need to be tailor-cut to the required shape before they can be stacked, folded, sealed and packaged into a battery.



Li-ion battery electrodes and separator foils

Mechanical cutting tools have typically been employed, but they present some critical challenges. One drawback is the formation of burrs across the electrode cut edge, which has the potential to cause shorting between foils. Another problem that grows over time is tooling wear. As a mechanical die wears down, the diminishing and inconsistent cutting quality can increase the risk of delamination and burr formation. Inevitably, when a mechanical die must be replaced (before the machine becomes unstable), production downtime could occur.

The good news is that there is an optimal solution for Li-ion battery manufacturing: lasers for cutting and welding. Lasers are very high precision devices and can perform accurately and repeatably on the order of microns—a feature becoming more important as batteries continue to get physically smaller and more compact. By contrast, traditional mechanical tools cannot reliably perform on nearly the same scale.

Lasers offer a range of features and sophistication for addressing new and challenging material compositions that will arise as battery technology evolves. They are easily deflected to variable and intricate cutting paths that are software-reconfigurable, in sharp contrast to the complete re-tooling that goes hand-in-hand with mechanical cutting. Lasers also produce higher quality cuts and welds than traditional tools do, thereby optimizing throughput and increasing product reliability. And for thin materials, laser welding is a very fast and flexible process, which is especially advantageous for changing shapes or form factors of batteries.

Furthermore, laser cutting and welding are contact-free operations, so there is no tool wear, and the replacement downtime is exceedingly infrequent by comparison to mechanical methods. MKS believes that incorporating lasers into Li-ion battery production will not only enable higher energy density designs but will also reduce manufacturing costs in the pursuit of $100/kWh and less.

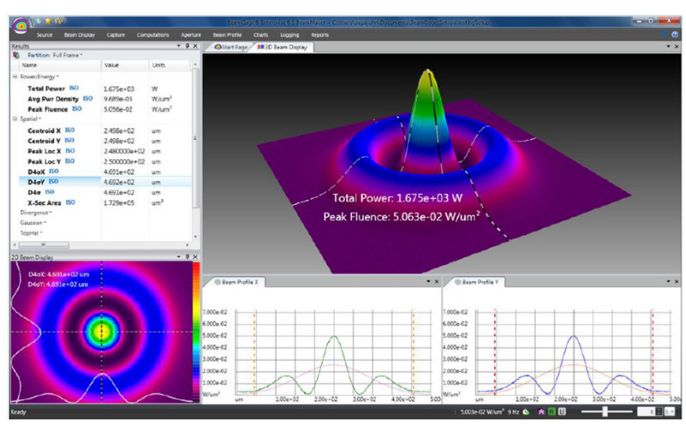
The MKS Advantage for Li-ion Battery Manufacturing

MKS understands the challenges faced in designing and building Li-ion batteries of all shapes and sizes. We've turned this knowledge into unique product features that provide an advantage when used in Li-ion battery manufacturing. Some of these features are described here.

Beam Analysis

Even with the advantages that lasers have over traditional tools, laser systems can still degrade over time. Some causes of degradation include thermal effects on a laser system's internal components, debris, vapors and spatter on the protective glass and vibrations or shock. These issues could affect laser performance in a number of ways. First, output power may be reduced, causing the laser to be less efficient. Another problem that may be caused is a change in the focus or other profile of the beam, which may lead to a cut or weld to be off target, not deep enough, low quality or possibly damaging to another part of the material.

Therefore, to ensure the highest quality of Li-ion battery manufacturing and to minimize the possibility of production downtime, it is crucial to monitor the laser beam frequently with appropriate instruments—like Ophir® power sensors, power meters and beam profilers—that can operate at the laser's wavelength while handling its maximum output power level.



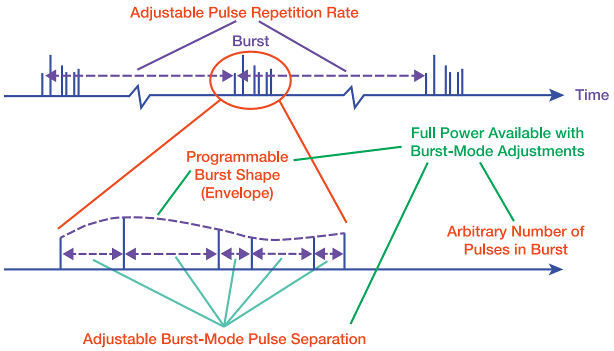
Ultrashort Pulse Lasers

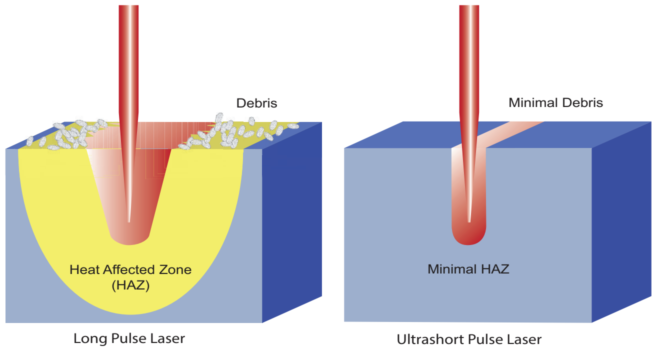
One of the challenges for laser materials processing is removing only the desired material, usually through localized heating, while at the same time minimizing the extent of the heat-affected zone (HAZ) to any of the remaining material. Delivering laser irradiation with near-perfect beam quality precisely to the target region is a necessary step to achieving this desired result. Ultrashort pulse widths in the picosecond through femtosecond range can be advantageous to achieving higher-quality results, as they yield intense peak powers that result in nonlinear absorption at the sample for instantaneous material vaporization, very minimal heat transfer into the material, and a negligible HAZ. The result is a fast, high-precision, high-quality operation which leads to higher throughput and fewer part failures.

Programmable Laser Burst Modes

Conventional ultrashort pulse lasers operating in single pulse mode are able to meet many requirements for precision micromachining. But to further improve quality and throughput, ultrashort pulse lasers with pulse flexibility or tailoring capability, such as the Spectra-Physics IceFyre®, should be employed. Pulse tailoring temporally splits pulses in the form of bursts with varying pulse spacing and customized pulse envelopes. Operating in this type of "burst mode" provides an additional degree of freedom for process optimization compared to single pulse mode.

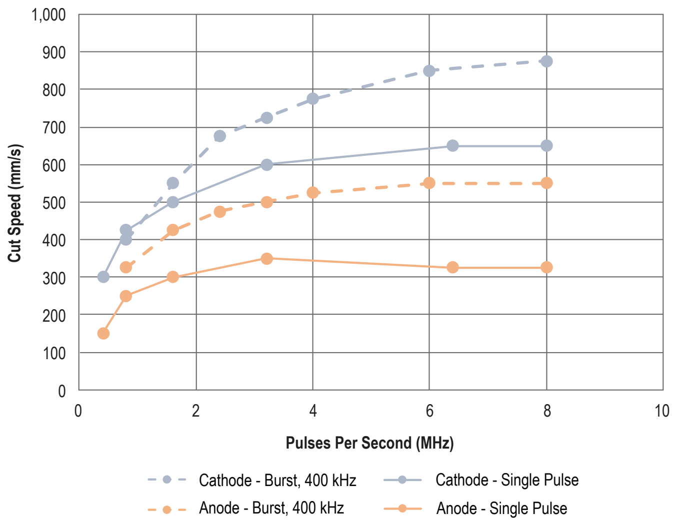
Engineers at MKS industrial applications lab have demonstrated the benefits of cutting Li-ion battery materials in burst mode. Samples of (1) a cathode material consisting of a ~16-µm-thick aluminum foil coated on both sides with lithium nickel manganese cobalt oxide (NMC) for a total thickness of ~100 µm and (2) an anode material consisting of an ~11-µm-thick copper foil coated on both sides with graphite for a total thickness of ~98 µm were cut in both single pulse mode and Spectra-Physics' proprietary *TimeShift*™ burst mode. The



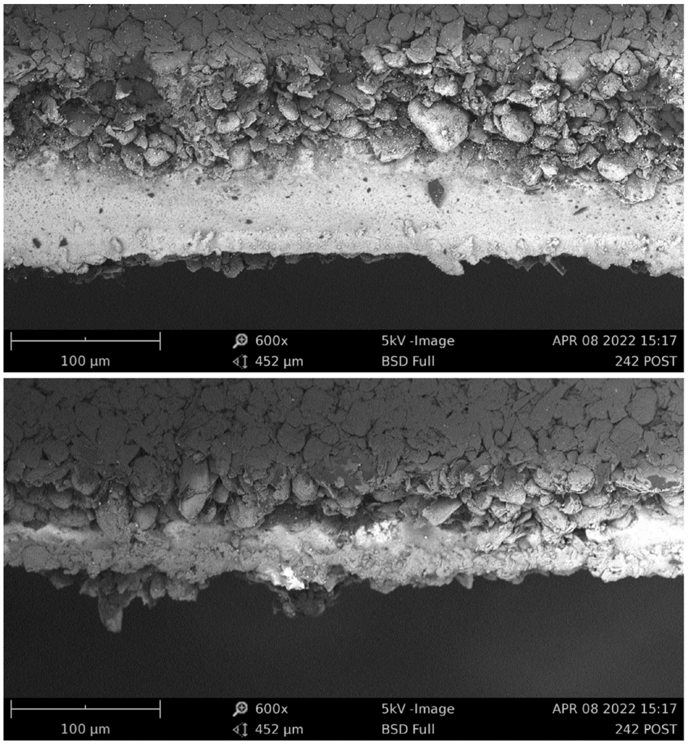


The impact of laser pulse width on machining quality for a long pulse laser (left) versus an ultrashort pulse laser (right).

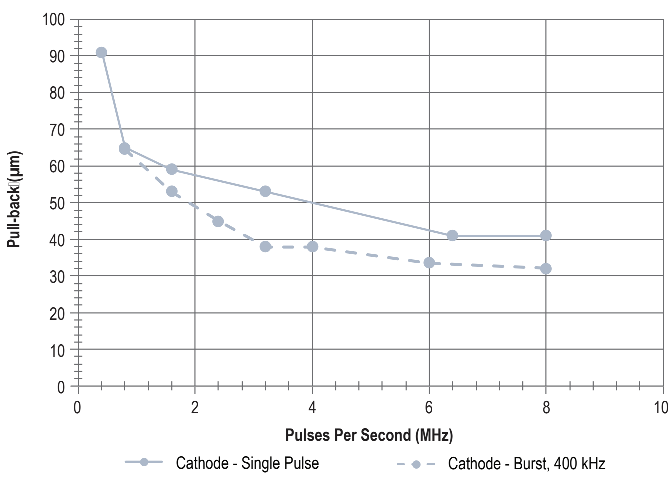
results are impressive. Burst mode delivered an increase in net cutting speed over single pulse mode of ~35% and ~57% for the cathode and anode materials, respectively. The quality of the cuts is also better in burst mode, as can be observed visually with SEM images of cut edges of anode material and up to a ~22% decrease in coating pull-back (i.e., the distance the coating has receded from the cut edge of the metal foil) shown for cathode material.



Net cut speed versus pulses per second for cut results comparing burst mode versus single pulse mode for cathode and anode foils



SEM images of anode foil cut edge. Sample was processed at 400 kHz using single pulse mode (top) and a burst of 20 pulses (bottom). Images show some protrusion of the metal foil as expected due to the coating pull-back, with greater pull-back in the unoptimized single pulse process. The foil is confined to its layer, showing minimal burr or smearing.



Electrode coating pull-back versus pulses per second for cut results comparing burst mode versus single pulse mode for cathode foils

MKS Products for Li-ion Battery Manufacturing

MKS offers many products that are broadly utilized in Li-ion battery manufacturing. For more information, please visit www.newport.com or call +1 877-835-9620. Also, visit www.spectra-physics.com

Industrial Laser Power Meters

Ophir Helios™ laser power meters are designed to be integrated into production stations to quickly measure high power industrial lasers. They measure the energy of a short time exposure to the power which allows measurement during loading and unloading of an assembly piece, and combined with a fast response time of 3 seconds, downtime is minimized or avoided. The compact, dust-resistant industrial body also features a cover to protect the sensor when not in use that can be opened and closed remotely. There is no need for water cooling, and an additional power meter is not required.

- Up to 12 kW power
- 900-1100 and 450-550 nm spectral ranges
- Not water cooled
- PROFINET, Ethernet/IP, EtherCAT and RS-232 options

Industrial Laser Beam Profiler

The Ophir BeamWatch® Integrated beam profiler is a fully automated measurement system that integrates the measurement of critical laser beam parameters onto industrial production lines. Our patented non-contact measurement system based on Rayleigh scattering enables real-time measurement of very high-power IR lasers without disruption of the beam. Parameters that can be measured include waist (focus spot) width and location, focal shift, divergence, M², absolute power and others. Short measurement times allow laser beams to be checked automatically during the loading and unloading phase.

- Patented non-contact measurement for real-time monitoring of critical beam parameters
- Up to 10 kW power (or 30 kW on request)
- 980-1080 nm spectral range
- GigE, PROFINET, Ethernet/IP, and CC-Link options

Beam Profiling Cameras

Another effective way to analyze beam profile is with a camera-based system. Ophir beam profiling cameras allow real-time viewing and measuring of a laser's structure in high resolution. Camera-based systems can also measure cross-sectional intensity of the laser and provide a complete 2-dimensional view of the laser mode.

- Spectral ranges from UV to mid-IR
- High-resolution, real-time viewing
- Highest accuracy measurements
- User-friendly application software with extensive analytical features included

High Power Thermal Sensors

MKS offers an extensive set of Ophir high power thermal sensors for IR wavelengths. Included among the sensors is the highest power measurement capability in the market (up to 120 kW) and the highest damage threshold available (up to 10 kW/cm^2 at full power). Typical response times are on the order of a few seconds. Ophir sensors and meters meet the ISO/IEC 17025 standard for calibrated devices.

- kW range power measurement
- IR spectral ranges
- Very high damage thresholds
- Fast response times

Picosecond IR Laser

The Spectra-Physics IceFyre ps IR laser sets a new standard for ps micromachining and can provide the ultimate solution for anode and cathode cutting. With up to 50 W of output power and typical ultrashort pulse widths of less than 15 ps, IceFyre ps can cut quickly with negligible HAZ. Moreover, IceFyre's unique design exploits fiber laser flexibility and Spectra-Physics' exclusive power amplifier capability to enable *TimeShift* programmable burst-mode technology for the fastest cutting speed and highest quality processing. Based on Spectra-Physics' *It's in the Box*™ design, the laser and controller are integrated into a single, compact package, and IceFyre is manufactured to provide 24/7 industrial reliability

- Up to >50 W power
- Typical pulse widths <15 ps
- Single shot to 10 MHz repetition rate range
- Proprietary *TimeShift* burst-mode technology for unprecedented pulse control

Femtosecond IR Laser

Spectra-Physics' IceFyre fs IR laser is an extraordinary leap forward in 24/7 industrial micromachining, delivering industry-leading performance, versatility, reliability and cost of ownership. It is ideal for high throughput, highest quality cutting of anode and cathode foils. Tests have shown that this laser can cut 100-μm-thick graphite-coated copper foil at 1.4 m/s speed with negligible HAZ and minimum burrs. IceFyre fs IR can also cut separator foil—fully cutting through 20-μm-thick PE separator foil at 15 m/s speed with negligible HAZ and less than 10-μm chipping has been demonstrated.

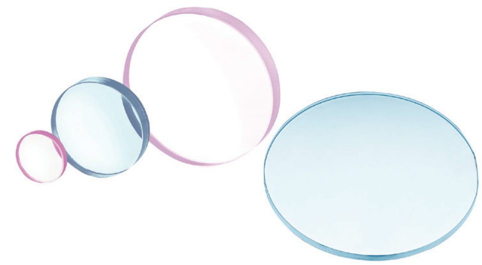
- Up to >200 W power
- Typical pulse widths <500 fs
- Single shot to 50 MHz repetition rate range
- Proprietary *TimeShift* burst-mode technology for unprecedented pulse control

DPSS Q-Switched UV and Green Lasers

For separator foil cutting, Spectra-Physics' Talon® diode-pumped solid state (DPSS) Q-switched UV lasers are ideal. Delivering up to 45 W of UV output power with nanosecond range pulse widths, Talon has demonstrated the ability to cut separator foils at over 1 m/s speed while producing less than 25-micron HAZ. Additionally, Talon UV and green lasers can cut through coated metal foil electrodes with very good quality and narrow cut widths. All Talon lasers feature our proprietary E-Pulse™ technology, which holds pulse energy and pulse width constant over wide repetition rate ranges to ensure outstanding process control. Based on Spectra-Physics' *It's in the Box*™ design, the laser and controller are integrated into a single, compact package, and the rugged industrial design can supply the long-term performance and low cost of ownership necessary for a 24/7 precision manufacturing tool.

- Up to >45 W (UV) and >70 (green) power
- Typical pulse widths <25 ns, <35 ns or <43 ns
- 0-500 or 700 kHz repetition rate
- Proprietary E-Pulse technology for superb process control

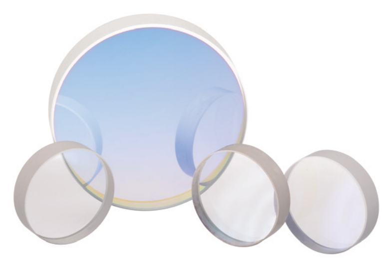
1-Micron Optics



Utilizing advanced manufacturing methods, MKS produces Ophir 1-micron optics specifically for use with high power IR fiber lasers. These optics' high laser induced damage threshold (LIDT) coatings on high-purity UV grade fused silica substrates can withstand up to 20 J/cm^2. Fiberlens™ aspherical lenses in various shapes can be provided in custom configurations. Conventional singlet and doublet spherical lenses and protective windows are also available. In addition, collimating and focusing assemblies and motorized zoom lenses for laser cutting heads are offered as standard products or as OEM custom designs.

- Spherical and aspherical lenses
- Protective windows
- Collimation and focusing assemblies
- Motorized zoom lenses for cutting head
- LIDT up to 20 J/cm^2

High-Energy Laser Optics



Dozens of Newport standard catalog optics are designed to operate with high-energy lasers such as those used in Li-ion battery manufacturing. Mirrors, lenses, beam splitter cubes and waveplates are readily available in various sizes and shapes whose substrate materials and coatings are optimized for UV, green and IR wavelengths. These high-performing optics can withstand high laser fluences to enable many solutions for Li-ion battery manufacturing.

- Mirrors, lenses, beam splitter cubes, waveplates
- Optimized for UV, green and IR wavelengths
- Extensive ultrafast optics selection
- LIDT of up to 45 Joules per cm^2
- Various sizes and shapes

WHY MKS?

CRITICAL TECHNOLOGIES

World-class technology and development capabilities for leading-edge processes

PROVEN PARTNER

Recognized leader delivering innovative, reliable solutions for our customers' most complex problems

OPERATIONAL EXCELLENCE

Consistent execution across all aspects of our business

COMPREHENSIVE PORTFOLIO

Largest breadth of product and service solutions for the markets we serve

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Newport is a brand within the MKS Instruments Light & Motion division. The Newport product portfolio consists of a full range of solutions including precision motion control, optical tables and vibration isolation systems, photonic instruments, optics and opto-mechanical components. Our innovative Newport solutions leverage core expertise in vibration isolation and sub-micron positioning systems and opto-mechanical and photonics subsystems, to enhance our customers' capabilities and productivity in the semiconductor, industrial technologies, life and health sciences, research and defense markets.

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