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**Fig. 1** Large-area ion beam sputtering (IBS) coating system for substrates up to 550 mm in diameter. Shown is the handling of a beam transport mirror for the HAPLS petawatt laser at ELI Beamlines.

## Advanced coated optics for high-energy laser systems

Complex sputtered dielectric coatings enable high LIDT, low losses, and dispersion control for apertures up to 550 mm.

Thomas Willemsen, Melanie Gauch, Tobias Groß, Henrik Ehlers, and Wolfgang Ebert

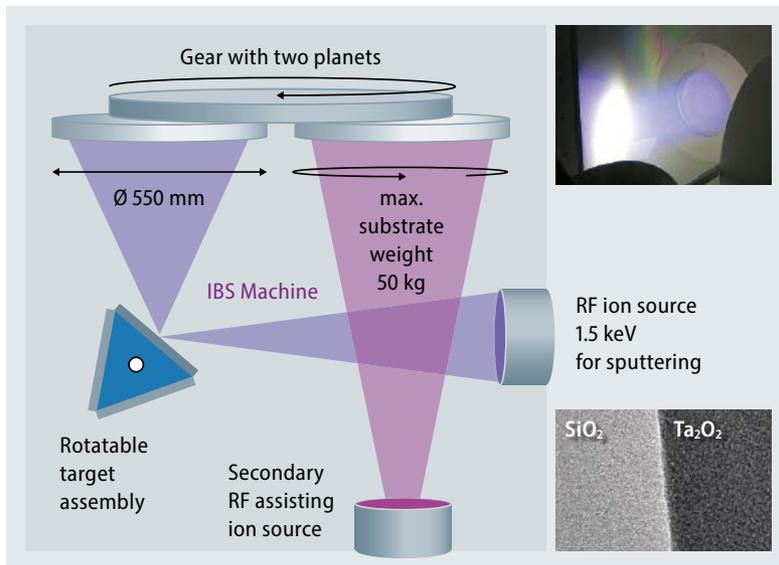
Petawatt laser beamlines have become essential tools for fundamental research in extreme-field and plasma physics and serve as the technological foundation for inertial laser fusion. These systems and their needs impose extreme requirements on coated optical components, demanding large apertures that combine high laser-induced damage threshold, low optical losses and precise dispersion control. This article discusses how sputter-deposited dielectric coatings on substrate

sizes up to 550 mm enable reliable optical performance in petawatt laser beamlines like ELI and how the same coating precision supports broadband dielectric mirrors for astronomical applications.

The performance of modern high-energy laser systems is increasingly determined by the optical components used to guide, shape and focus the beam. In particular, petawatt-class laser facilities operating with ultrashort pulses at extreme

peak intensities impose unprecedented demands on coated optics. These systems enable fundamental research in plasma physics, high energy-density science and extreme-field physics and form the technological basis for long-term applications such as inertial laser fusion.

Compared with earlier generations of high power lasers, today's petawatt beamlines combine extremely high fluence levels with stringent requirements for dispersion control, wave front quality, and long term stability. As beam



**Fig. 2** Concept of the large ion beam sputtering system. Sputtered layers are very hard and dense.

diameters increase, coated optics must maintain uniform optical performance across large apertures while remaining mechanically stable under repeated vacuum-to-air cycling.

Large-aperture mirrors must therefore simultaneously provide high laser-induced damage threshold, low optical losses and a stable reflected wavefront over the full clear aperture. Meeting these combined requirements turns coated optics into key enabling elements that directly determine the performance and reliability of modern petawatt laser beamlines (Fig. 1).

### Why modern laser mirrors require complex dielectric coatings

The performance requirements of modern petawatt laser beamlines cannot be fulfilled by conventional mirror coatings alone. Instead, laser mirrors must be engineered as complex dielectric systems that address damage resistance, dispersion control and optical losses within a single coating design.

In ultrashort-pulse laser systems, dispersion control is essen-

tial to preserve pulse duration and peak intensity at the target, while broadband high reflectivity is required to support short pulse durations. At the same time, optical losses and surface impurities must be minimized to avoid local heating and performance degradation. These requirements are closely interlinked and cannot be optimized independently.

As apertures increase, maintaining uniform optical performance across the full clear aperture becomes increasingly challenging. Consequently, modern laser mirrors rely on advanced dielectric coating architectures that go beyond simple quarter-wave layer stacks, enabling broadband performance, controlled dispersion and high damage resistance within a mechanically stable coating system.

### Manufacturing complex dielectric coatings on large optics

Translating complex dielectric coating designs into reliable optical components when scaling to large apertures becomes particularly challenging. High-energy laser ap-

plications require coated optics with diameters of several hundred millimeters while maintaining uniform reflectivity, dispersion and wavefront performance across the entire clear aperture.

Large-aperture coated optics demand precise control of coating thickness distribution and mechanical stress to avoid wavefront deformation and long-term instability. In addition, coating processes must offer high reproducibility to ensure consistent optical performance from component to component.

Highly controlled sputter-based deposition techniques are well suited to meet these demands, as they enable dense dielectric layers with well-defined optical and mechanical properties (Fig. 2). The ability to reproducibly manufacture complex dielectric coatings on apertures up to 550 mm forms the technological foundation for large mirrors that combine high laser-induced damage threshold, low optical losses and controlled dispersion for demanding laser applications.

### High-LIDT coated optics for fusion and petawatt laser beamlines

High-energy petawatt laser beamlines impose some of the most demanding requirements on coated optical components currently found in photonics. Large-aperture mirrors must guide ultrashort laser pulses with extreme peak intensities while maintaining reliable long-term operation under vacuum conditions.

For fusion-oriented laser systems and petawatt-class research facilities, the laser-induced damage threshold is a key performance parameter. However, high damage resistance alone is not sufficient. Coated optics must simultaneously provide broadband reflec-

tivity, controlled dispersion, low optical losses and stable wavefront performance over large apertures depending on the pulse range of the laser. Mirror specifications therefore can differ depending on whether the laser operates in continuous-wave, nanosecond, or ultrashort-pulse regimes.

In practical beamline operation, additional challenges arise from vacuum compatibility and long-term stability. Conventional coatings on large fused silica substrates have shown susceptibility to stress-induced crazing or performance drift during repeated vacuum-to-air cycling. Dense sputtered dielectric coatings provide improved mechanical stability and reproducible optical performance under realistic operating conditions.

The successful implementation of high-LIDT coated optics on large apertures enables reliable beam transport in petawatt laser facilities and supports both fundamental research and the development of next-generation fusion-class laser systems. This was enabled by scaling up the homogeneous coated area in a sputtered process by constructing a special planetary gear system.

### Low-loss and defect control as a prerequisite for high damage resistance

Reliable operation of high-energy laser beamlines is not only determined by peak fluence or coating design but is critically influenced by optical losses and defect-related damage mechanisms. In the nanosecond pulse regime, laser-induced damage is predominantly defect-driven. Localized absorption or scattering at defects can lead to thermal runaway and damage initiation even when average loss levels appear low.

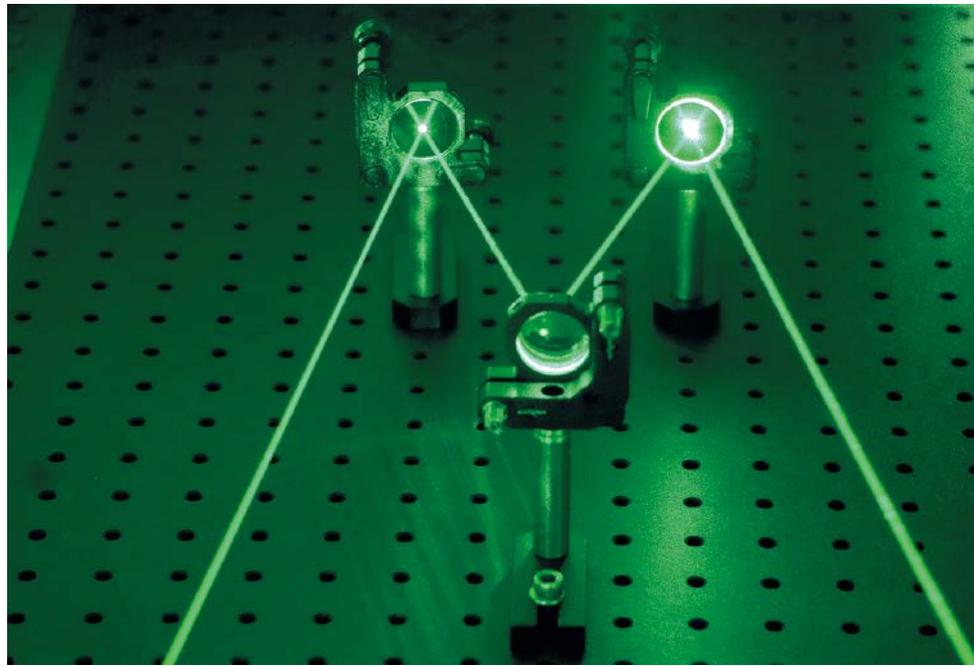


Fig. 3 Low-loss IBS mirrors deposited on standard and super-polished substrates

As beam diameters increase in high-energy laser systems, defect control becomes increasingly challenging. A larger beam footprint statistically interacts with a higher number of coating and substrate defects compared to small-aperture test beams.

As aperture size increases, the probability of encountering critical defects rises, making scalability a central challenge for large area coated optics. Ensuring defect-free performance across large apertures therefore requires both extremely low defect densities and reliable strategies for identifying critical defects.

Low-loss performance and defect control must be regarded as system properties that depend on the combined quality of substrate preparation and coating process (Fig. 3). High-quality polishing of fused silica substrates is essential to minimize surface roughness and sub-surface damage, which can act as precursors for defect formation. At the same time, the coating process itself must produce dense di-

electric layers with minimal intrinsic defect density.

Highly controlled sputter-based deposition processes can enable the fabrication of dense dielectric coatings with reduced inclusion and defect densities compared to conventional evaporation techniques. Such processes are particularly well suited for applications where nanosecond damage resistance and long-term stability are critical. In addition, reproducible coating processes facilitate the identification and characterization of critical defects, providing valuable feedback for both substrate preparation and coating optimization.

While defect statistics and damage mechanisms are often investigated using small-aperture reference samples, the underlying physical processes directly translate to large-area optics. Controlling losses and defect densities at the microscopic level is therefore a prerequisite for achieving reliable high-damage-threshold performance on the large apertures required in modern high-energy laser beamlines.



**Fig. 4** Broadband dielectric mirror for astronomical applications. The large reflected spectral width gives the mirror a metallic appearance.

### Ultrafast coated optics: deterministic damage mechanisms and dispersion control

In contrast to nanosecond laser-induced damage, which is largely governed by defect-driven absorption and thermal processes, damage mechanisms in the ultrashort pulse regime follow a fundamentally different physical picture. For femtosecond and picosecond laser pulses, laser-induced damage is dominated by electronic excitation processes rather than by heat accumulation. Multiphoton absorption, tunnel ionization and subsequent avalanche ionization play central roles in the damage process, which strongly depends on the intrinsic electronic properties of the coating materials.

As a result, laser-induced damage in the ultrafast regime becomes more deterministic and closely linked to the band structure of the dielectric materials, including

the valence and conduction band characteristics and the effective bandgap. Material selection and precise control of the electric field distribution within the coating stack therefore become critical design parameters for ultrafast coated optics.

In high-energy ultrashort-pulse laser systems, such as petawatt-class beamlines and high repetition rate ultrafast lasers, dispersion control represents an additional key requirement. Coated optics must provide well-defined group delay dispersion while maintaining high damage resistance and low optical losses. Advanced dielectric coating concepts, including chirped mirrors and Gires-Tournois interferometer designs, enable tailored phase response over broad spectral bandwidths and are essential for preserving pulse duration and peak intensity throughout the beamline. Such designs can only be realized using sputter-based deposition processes. The combination of the reliable and reproducible sputter process and application of high-end monitoring technique during deposition – an optical broad band monitor – make thickness precision in the sub-nanometer regime feasible.

Although damage mechanisms in the ultrafast regime are less sensitive to isolated defects than in nanosecond applications, defect control and substrate quality remain essential. Surface roughness, subsurface damage and coating inhomogeneities can lead to local field enhancement and scattering, influencing both damage behavior and dispersion performance. Consequently, defect-free dielectric layers and well-polished substrates are a prerequisite for reliable ultrafast coated optics, particularly when scaling to larger beam diameters.

The ability to combine deterministic ultrafast damage behavior with low-loss, defect-controlled di-

electric coatings on large substrates provides a direct link to broadband mirror concepts used in other applications. Many of the same design principles – dense dielectric layers, precise thickness control and low intrinsic losses – also underpin complex broadband dielectric mirrors, including those developed for astronomical instrumentation.

### Broadband dielectric mirrors for astronomical applications

While laser-induced damage threshold is the dominant performance driver in high-energy laser beamlines, astronomical applications impose a different set of priorities on coated optics. Large mirrors used in telescopes and astronomical instrumentation require high reflectivity over broad spectral ranges combined with very low optical losses and long-term stability. In these systems, absorption and scattering losses directly impact signal quality and sensitivity, making low-loss performance a key figure of merit.

Historically, broadband mirror requirements in astronomy have been addressed using metallic coatings due to their inherently wide spectral coverage. However, metallic layers exhibit comparatively high absorption losses and limited maximum reflectivity, which can restrict overall optical efficiency. Dielectric mirror coatings offer significant advantages in terms of reflectivity, durability and environmental stability, but realizing broadband dielectric performance requires complex multilayer designs with precisely controlled layer thicknesses.

The fabrication of such complex broadband dielectric coatings is only feasible using highly controlled sputter-based deposition processes. Ion beam sputtering enables the production of dense, low-loss dielectric multilayer systems with excellent thickness accuracy, mak-

ing it possible to achieve broadband spectral performance that cannot be achieved with conventional coating techniques. This capability is particularly important when transferring broadband dielectric designs to large optical components.

Advanced coating platforms allow these complex dielectric mirrors to be manufactured on large and even curved substrates with diameters exceeding 500 mm. As demonstrated by broadband dielectric optics with diameters of about 520 mm, uniform coating performance can be achieved across large apertures and curved surfaces alike (Fig. 4). This scalability provides a significant advantage over metallic coatings, enabling broadband dielectric mirrors that combine low losses, high reflectivity and mechanical stability on optics of practical astronomical size.

The successful realization of large-area broadband dielectric mirrors demonstrates how the same coating precision and defect control developed for high-energy laser applications can be transferred to astronomy. In this context, low-loss performance and coating uniformity, rather than damage resistance, define the key performance parameters and highlight the versatility of advanced dielectric coating technologies.

The discussed examples demonstrate that advanced ion beam sputtered dielectric coatings enable reliable optical performance across a wide range of demanding applications. Large-area coated optics manufactured using highly controlled sputter-based processes support both nanosecond and ultrashort-pulse petawatt laser beamlines, where high damage

resistance and defect control are critical. At the same time, the same coating precision provides decisive advantages for broadband, low-loss dielectric mirrors in astronomical instrumentation, highlighting the versatility of advanced coated optics on large apertures.

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