EUV Plasma Source with IR Power Recycling

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Abstract

Laser power requirements for an EUV laser-produced plasma source can be reduced by using power-recycling optics to reflect plasma-scattered IR radiation back onto the plasma. Previously proposed spherical retro-reflective mirrors can be used to form an inverted image of the plasma on itself, but an erect (non-inverted) image would be more tolerant of positional alignment errors. Erect-imaging optical design alternatives for power recycling are described in this paper.

Introduction

A laser-produced plasma (LPP) produces extreme ultraviolet (EUV) radiation from high-energy ionization of a laser-vaporized target such as a tin droplet. Typically, a stream of tin droplets is irradiated by a pulsed CO_2 laser at a 10.6-μm wavelength, producing EUV radiation at wavelength 13.5 nm. The EUV output is focused by an elliptical collector mirror onto an intermediate focus (IF).

Ref's. 1 and 2 describe power-recycling collector optics, which reduce laser power requirements of an LPP source by retro-reflecting plasma-scattered IR back onto the plasma. A limitation of these systems is that they form an inverted image of the plasma on itself, which makes the system sensitive to positional misalignment between the plasma and retro-reflector (e.g., a positional displacement of the plasma causes its self-image to move in the opposite direction, away from the plasma). Ideally, the system would produce an erect (non-inverted) plasma image, which would tend to follow any positional variations of the plasma relative to the imaging optics. This paper describes two types of erect-image retro-reflector systems: a cat's-eye lens/mirror array and a corner-cube mirror array.

Cat's-Eye Array

Figure 1 illustrates a variation of Figure 5 in Ref. 2 in which the spherical retro mirrors are double-shell reflectors, each comprising a transmitting inner shell and a reflecting outer shell. The enlarged detail view in Figure 1 shows a cross-sectional view a double-shell reflector. An array of converging lenses on the inner shell images the plasma onto foci on the outer shell, and an array of concave mirrors on the outer shell retro-reflects the plasma images back through the lenses. Each lens is paired with a corresponding mirror, and the two in combination operate as a cat's-eye retro-reflector. Accurate retro-reflection is maintained even as the plasma position varies (as indicated by the dashed ray lines and direction arrow in Figure 1).

Typical lens diameters would be larger than 10 mm. At the 10.6-μm IR wavelength, this would result in a diffractive spread less than 1 mrad, which is comparable to the plasma subtend angle at the retro-reflector. Smaller lenses could possibly be used if they are accurately constructed and aligned to preserve phase coherence at the plasma center point.

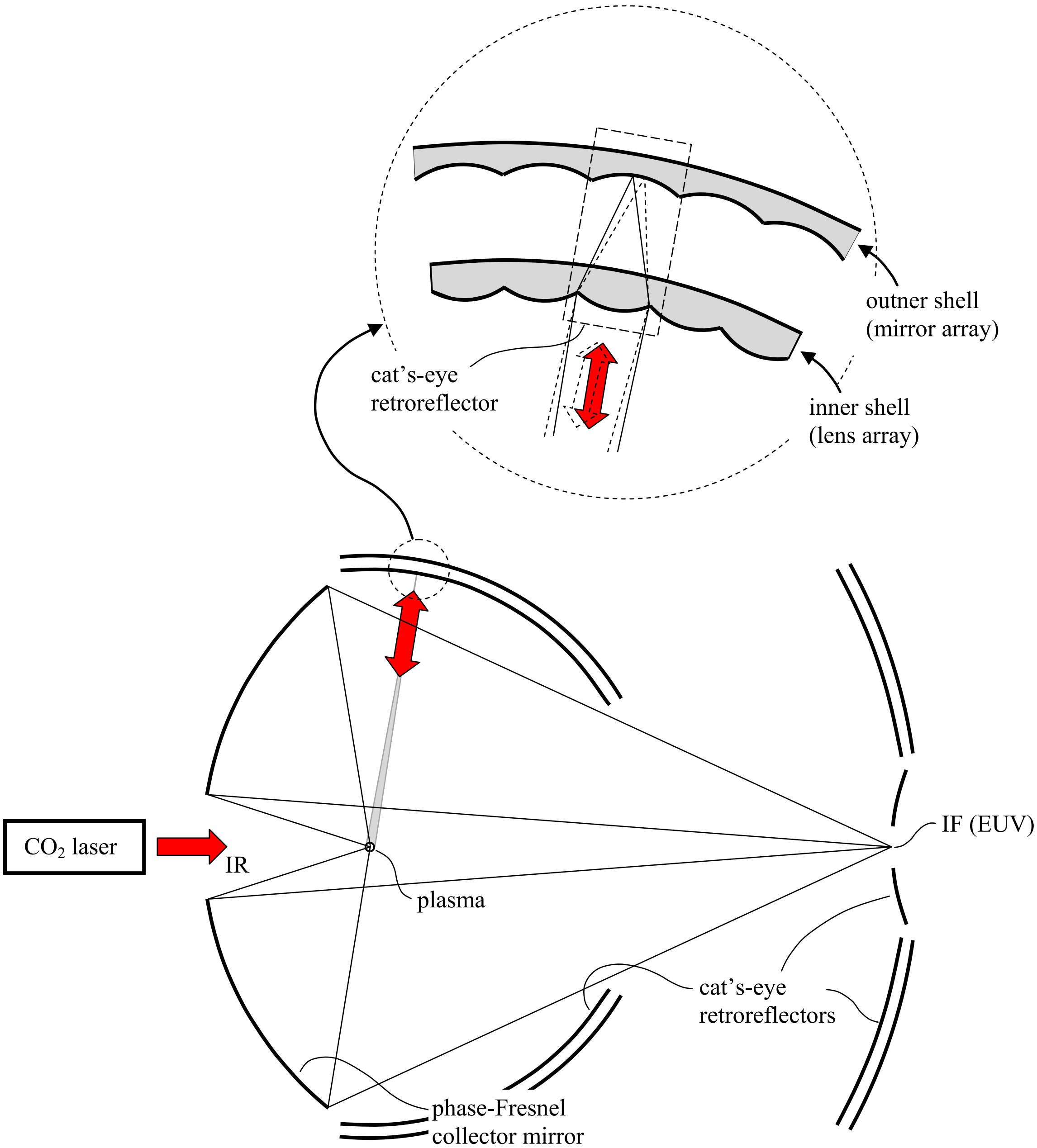

Figure 1. IR power recycling with cat's-eye retroreflectors.

The Figure-1 configuration can be simplified in several ways. The space between the two shells could be filled with solid dielectric material, in which case the outer shell would simply be a reflective mirror coating formed on the inner shell's back side. The lenses and mirrors can be replaced by phase-Fresnel elements (e.g. using a lithographic patterning process). The spherical-shell substrates can be replaced by flat plates, using off-axis lenses or mirrors to accommodate off-axis illumination on the plates' peripheral region. For example, Figure 2 shows a cross-sectional view of a flat-plate design using phase-Fresnel lenses and off-axis, phase-Fresnel mirrors.

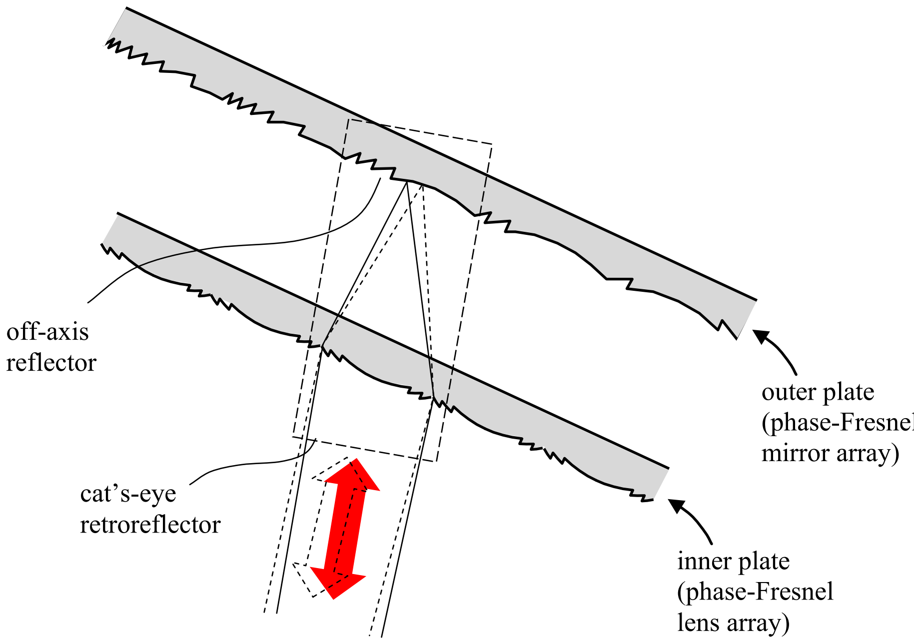

Figure 2. Flat-plate cat's-eye retroreflector design with phase-Fresnel optics.

The curved mirror elements are not necessarily required. Figure 3 illustrates a flat-plate design using off-axis lenses and a flat mirror surface. Each lens focuses the plasma's center point into a convergent light cone, with the cone axis is normal to the mirror. There may be some slight vignetting of the reflected light cone by the lens aperture when the plasma position changes, but accurate plasma self-imaging will still be maintained.

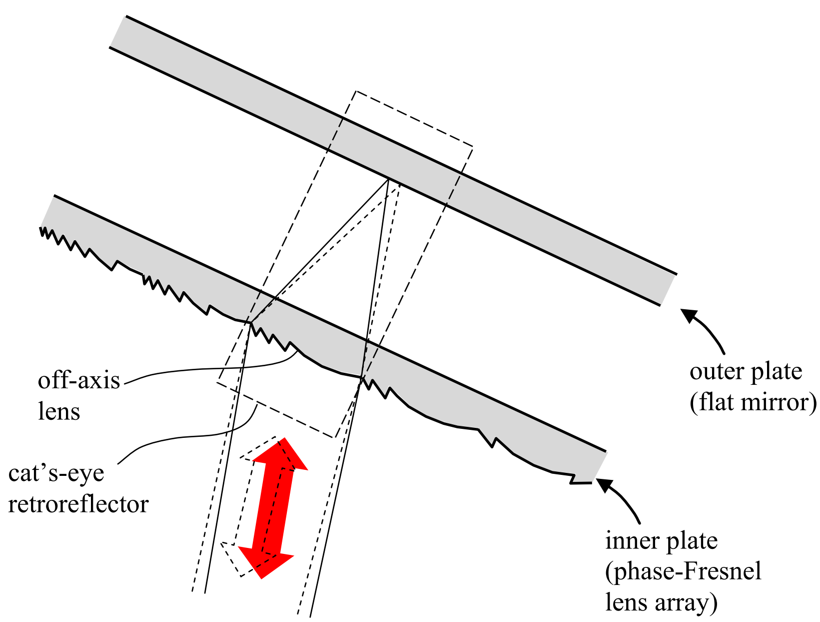

Figure 3. Cat's-eye retroreflector array with flat mirror.

Corner-Cube Reflector Array

Figure 4 shows another variation of Figure 5 in Ref. 2 in which the spherical retro mirrors comprise corner-cube retroreflector arrays. The mirrors are illustrated schematically by a sawtooth profile, but each retroreflector is a three-surface, corner-cube element.

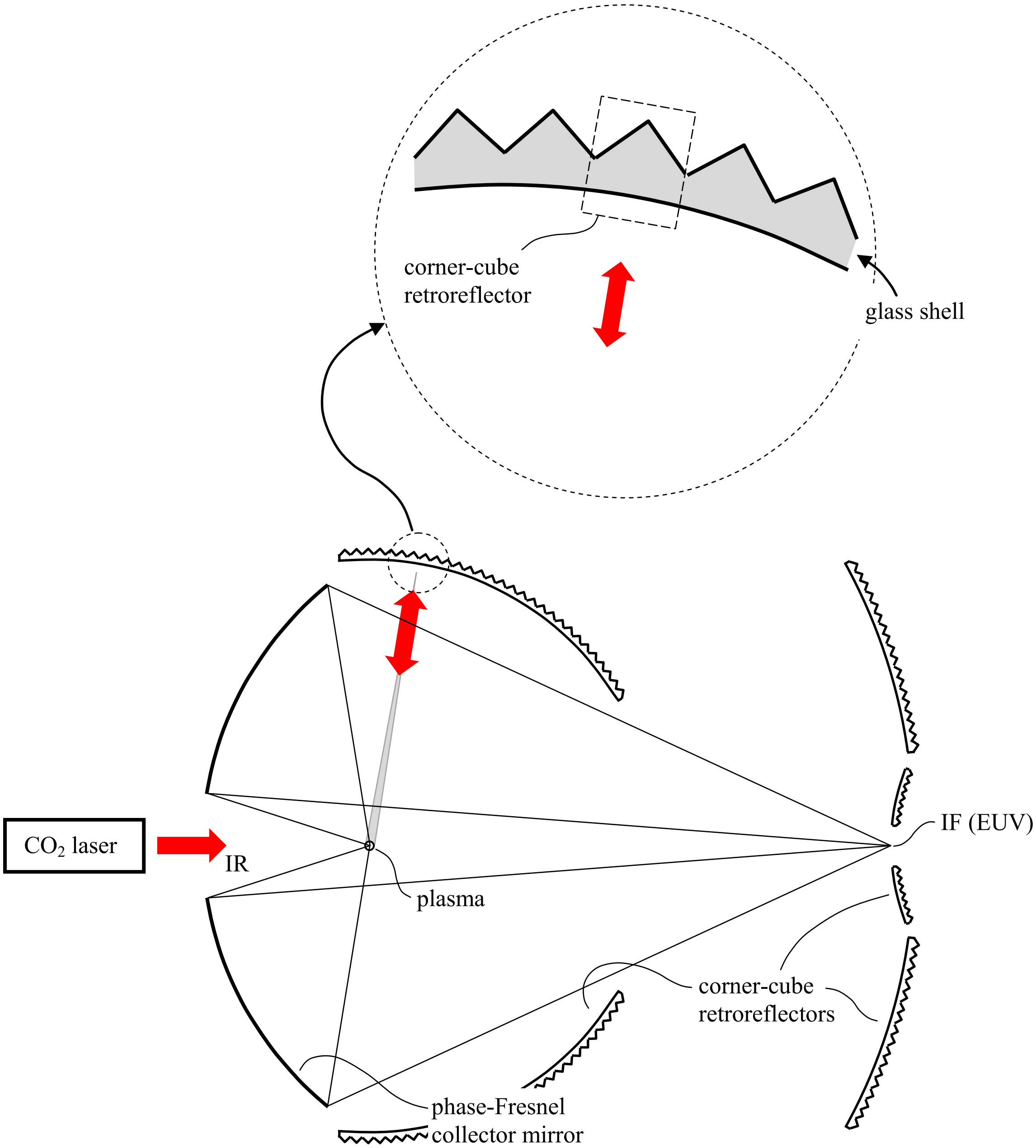

Figure 4. IR power recycling with corner-cube retroreflectors.

Figure 5 illustrates a portion of a conventional corner-cube array, one element of which is shaded. (From this perspective the incident beam reflects off the top of the array.) Each corner cube's three reflective surfaces are planar and mutually orthogonal. The device operates to retro-reflect a collimated beam directed approximately parallel to an optical axis, which is oriented at the same angle (approximately 54.7°) to all three reflector surface normals.

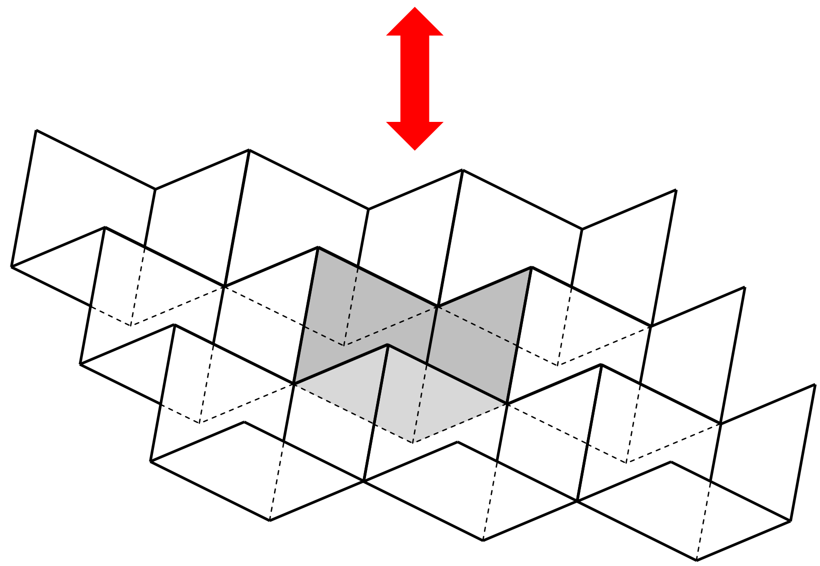

Figure 5. Corner-cube retroreflector array.

A conventional corner-cube design can be modified to achieve accurate self-imaging of an axial point at finite conjugate by making the reflector surfaces slightly concave, as described in Ref. 3 (e.g. see Figure 4 in Ref. 3). The surface geometry has sufficient degrees of freedom to achieve perfect geometric self-imaging of the plasma center point (although the optimal surface shape might not be exactly spherical as described in Ref. 3). Off-axis aberrations would be insignificant in comparison to the plasma size, provided that the reflector elements are sufficiently small. (The corner-cube aperture size would typically need to be larger than 10 mm to avoid excessive aperture diffraction, but smaller apertures could be used if the reflected beams are phase-coherent at the plasma center point.)

The enlarged detail view in Figure 4 shows a cross-section of a corner-cube array formed in a solid glass shell with the reflectors formed on its back side. This type of device requires no reflective mirror coating; it can operate via total internal reflection. Alternatively, front-surface reflectors could be formed as recessed, pyramidal cavities with metal or dielectric-coated reflector surfaces.

Figure 6 illustrates an alternative to the Figure-4 configuration, which uses conventional, flat-face corner cubes. Collimating lenses (e.g. a phase-Fresnel elements) on the reflector shell's inner surface collimate rays from the plasma center point, and these rays are retroreflected by the corner-cubes. If front-surface reflectors are used, then the collimating lenses can be formed on a separate, inner shell. (An advantage of this design over the Figure-1 double-shell configuration is that the shells need not be widely separated to accommodate the lens focal lengths.)

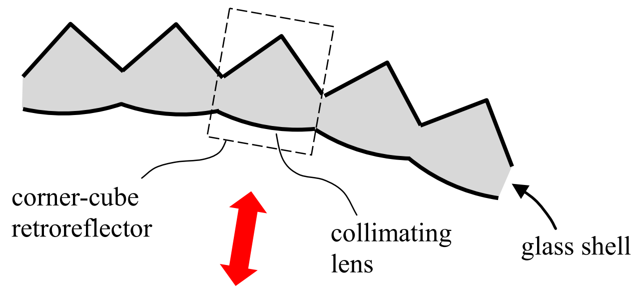

Figure 6. Flat-face corner-cube retroreflectors with collimating lenses.

The corner-cube arrays can be formed on flat plates analogous to the flat-plate cat's-eye design of Figure 2. In this case the corner-cube optical axes would be tilted relative to the plate normal over the peripheral portions of the plate to accommodate the incident beam divergence. Alternatively, off-axis collimating lenses can be used to direct the beams normal to the plate, allowing the use of a uniformly periodic array of flat-face corner cube reflectors.

A corner-cube reflector array can be fabricated by tiling an array of hexagonal-section bar segments, each of which has three precision-machined and polished corner-cube reflector surfaces on its end. The bar segments can be fused or bonded to a common substrate, or can be used as a replication master for manufacturing the reflector array (e.g. by molding or electroplating).

Integration with Spectral Purity Filter

Either a cat's-eye or corner-cube reflector design can be used for the retro mirror in the spectral filter system illustrated in Figure 6 of Ref. 2. (In this case the incident rays on the retro mirror are convergent to point P in the figure, so the collimating lenses in the corner-cube configuration of Figure 6 herein would be concave, negative-power elements on a convex glass shell.)

The grating line density on the periphery of the phase-Fresnel collector mirror can be reduced by designing some spherical aberration into the focused IR beam, as illustrated in Figure 7. IR rays reflected from the collector mirror near the center (at radius $R_{\min}$) intercept the optical axis at point P, as in Figure 6 of Ref. 2. But rays reflecting from the periphery (at radius $R_{\max}$) cross the axis at point P', closer to the IF. (Other rays cross the axis at intermediate points.) This reduces the angle between the reflected IR and diffracted EUV rays, resulting in a lower grating line density. The tradeoff to this advantage is that the reflector will need to operate over a greater angular range, possibly resulting in compromised power recycling performance.

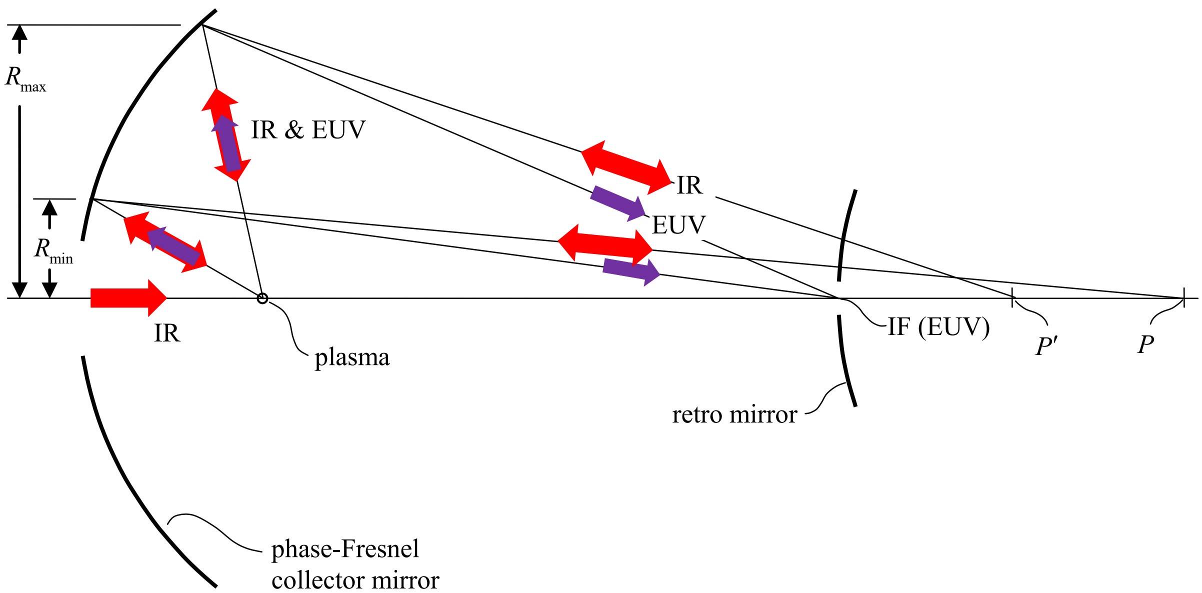

Figure 7. Spectral filter with spherically aberrated IR focus.

References

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