System Requirements Document: Laser-Cutting Machine for Metal Processing

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Revision History

Rev #	Date	Author	Description
1.0	2026-Apr-15	Asaf Granot	Initial Version
1.1	2026-May-15	Asaf Granot	Initial top-level requirements & Top-Level Block Diagram
2.0	2026-May-20	System Engineering Team	Consolidated SRD integrating product req, architecture analysis, and design inputs. Resolved physics-based contradictions per priority: sysreq example > Claude-SRD > ChatGPT-Phase1.

Related Documents

Doc #	Title
000-000	Laser-Cutting Machine Product Requirements
000-001	Laser-Cutting Machine System Requirements (this document)
000-002	Laser-Cutting Machine System Design & Architecture Document
000-003	Candidate System Architectures Analysis

Acronyms & Terms

Acronym / Term	Description
BOM	Bill of Materials
BPP	Beam Parameter Product
CAM	Computer-Aided Manufacturing
CNC	Computer Numerical Control
CW	Continuous Wave

Acronym / Term	Description
DOF	Depth of Field
HMI	Human-Machine Interface
MTF	Modulation Transfer Function
OCT	Optical Coherence Tomography
OPC UA	Open Platform Communications Unified Architecture
SIL	Safety Integrity Level
TBD	To Be Decided in a Later Stage of the Project
UF	Ultrafast (picosecond/femtosecond) Laser
UPS	Uninterruptible Power Supply

Background

The purpose of this document is to detail the consolidated and de-conflicted system requirements for a laser-cutting machine for metal processing. This machine is intended to cut Aluminum and Stainless-Steel accurately and be integrated into a production line with loading and unloading platforms.

This is the first product in the laser-cutting industry for System & Optics, to be integrated with already existing machine-vision based solutions from Product-A and Product-B as feedback and control modules.

An analysis of the initial product requirement for a 35µm minimum feature size through a full 15mm material thickness revealed a fundamental physics conflict. A single conventional laser source cannot resolve 35µm features through thick sections. This document adopts the physics-based, thickness-dependent feature size specification as the only feasible path, and selects a Variable-BPP Fiber Laser with High-Precision Gantry (Architecture C) as the leading architecture.

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1. System Architecture

1.1 Top-Level Block Diagram

The system comprises the following top-level modules:

- **Laser & Optics:** 12kW Variable-BPP Fiber Laser, adaptive zoom cutting head, beam delivery fiber, OCT sensor, coaxial camera, photodiode array, pyrometer, assist gas delivery (N2 up to 25 bar, O2 up to 6 bar).
- **Control & Feedback:** Real-time CNC controller (Beckhoff TwinCAT XFC or ACS SPiiPlus), safety PLC (Pilz PNOZmulti 2 or Sick Flexi Soft), adaptive cutting control loop, multi-sensor data fusion.

- **Computing & Calculations:** CAM post-processor with BPP mode switching, nesting software, process parameter database, HMI (local touchscreen), IoT gateway/edge computer (OPC UA), remote monitoring capability.
- **Electronics & HW:** Servo drives (EtherCAT), ironless linear motors, absolute linear encoders, main power management (480VAC 3-phase), auxiliary power supplies (12VDC for focus motors), EMC zoning/shielding.
- **Plate Loading Mechanics:** Automated pallet changer/loader, batch platform (up to 25 plates), automated one-by-one loading.
- **Sample Mechanics:** Polymer concrete or mineral cast machine base, high-precision linear motor gantry (X, Y, Z axes), shuttle work table with replaceable slats, downdraft fume extraction plenum.

`[Placeholder for Top-Level Block Diagram]` *Diagram Description: The diagram illustrates the main material flow from Plate Loading Mechanics to Sample Mechanics, where the Laser & Optics module performs the cutting. The Control & Feedback module receives real-time sensor data from Laser & Optics and Sample Mechanics (position feedback) and sends commands to Electronics & HW, which drives all active components. Computing & Calculations interfaces bidirectionally with Control & Feedback for file processing, adaptive parameter adjustment, and data logging, and communicates externally via External Interfaces. External Interfaces for coolant, gas, and electrical power connect directly to the respective hardware modules.*

1.2 Selected Architecture: Variable-BPP Fiber Laser with High-Precision Gantry (Architecture C)

This architecture uses a single 12kW fiber laser with variable BPP. The beam can dynamically switch between a tight, high-brightness mode (BPP ~0.8-1.5 mm·mrad) for fine features on thin stock, and a wider, distributed mode (BPP ~4-8 mm·mrad) for thick-section cutting. This single-source design achieves the best possible feature sizes within physics limits without the complexity and cost of a dual-source hybrid system. Advanced process monitoring (OCT, coaxial camera, photodiodes, pyrometer, acoustic emission) enables real-time adaptive control for quality optimization.

Architecture Comparison:

Parameter	**Architecture A (Conventional CW Gantry)**	**Architecture B (Dual-Source Hybrid)**	**Architecture C (Variable-BPP Gantry) [SELECTED]**
Laser Type	6-8kW CW Fiber	4-6kW CW + 50-100W UF	6-12kW Variable-BPP Fiber
Min Feature (<0.5mm)	~80-100 µm	~30-40 µm	~35-50 µm
Min Feature (15mm)	~300-400 µm	~200-300 µm	~200-350 µm
Throughput	30-50 parts/hr	15-30 parts/hr	25-45 parts/hr
Positioning Accuracy	+/- 15-25 µm	+/- 3-5 µm	+/- 5-10 µm

Parameter	Architecture A (Conventional CW Gantry)	Architecture B (Dual-Source Hybrid)	Architecture C (Variable-BPP Gantry) [SELECTED]
BOM Cost	Within target	Exceeds target (2x+)	Within risk-adjusted range ($150-165K)
Development Risk	Low	Very High	Moderate

Recommendation: Architecture C is recommended for the best balance of feature capability, throughput, cost, and development risk.

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2. Laser-Cutting Machine Top-Level Flow

2.1 Main Material Flow

1. **Batch Loading:** An operator loads a batch of up to 25 raw metal plates onto the loading platform. Maximum batch height is 495mm (calculated as 25 plates × 15mm + spacers).
2. **Auto Plate Loading:** The automated loading system picks a single plate from the top of the batch and loads it onto the machine's shuttle work table. Minimum single-plate batch height is 0.5mm.
3. **Workpiece Registration:** The machine-vision system (Product-A/B integration) or an edge-finding camera routine detects the plate's precise position, orientation, and any distortion for dynamic path compensation.
4. **Cutting Process:** a. The CNC controller loads the CAM program for the nested parts on the plate. b. The gantry positions the cutting head at the first pierce point. c. The control system sets the laser BPP mode, power, assist gas type/pressure, and focus position based on the process parameter database for the specific material, thickness, and feature size. d. The adaptive cutting control loop executes the cut, actively fusing data from the OCT (kerf depth), photodiode array (backscatter/plasma), pyrometer (temperature), and acoustic emission sensor to adjust laser power, feed rate, gas pressure, and focus in real time (loop rate ≥4 kHz). e. For features requiring high precision, the system automatically switches to Fine BPP mode; for bulk cutting, it uses Standard or Power mode. BPP mode switching time is ≤50 ms.
5. **Part Unloading:** On completion of all cuts, the work table shuttles out (exchange time ≤60 seconds). Finished parts and the skeleton/scrap are offloaded. Slag/dross is collected in a drawer below the cutting zone.
6. The cycle repeats from step 2 for the next plate.

2.2 Calibration Processes Flow

1. **Scheduled or Event-Driven Trigger:** A calibration cycle is triggered automatically after a configurable time period, number of plates processed, or manually by the operator.

2. **Motors Auto-Calibration & Homing:** All motion axes perform a homing sequence. The system verifies positioning accuracy across the full work area using the coaxial vision system and a calibrated reference artifact. Axis error maps and thermal compensation tables are updated.
3. **Power Auto-Calibration:** The laser fires at a defined power setpoint onto a built-in laser power meter that is split off from the main beam. The system verifies the measured power against the setpoint and adjusts the laser driver to maintain accuracy of +/- 0.5%.
4. **Nozzle Auto-Centering:** The coaxial vision system is used to automatically calibrate the nozzle center relative to the laser beam axis.
5. **Calibration Complete:** The system transitions back to a "Ready" state for production. All calibration data is logged and timestamped.

2.3 Error Handling

- **Real-Time Process Faults (e.g., excessive backscatter, pierce failure, kerf depth deviation):** The adaptive control loop immediately attempts a recovery strategy (e.g., reduce feed rate, increase gas pressure, adjust focus). If recovery is not achieved within a configurable timeout, the laser is shuttered, motion is paused, and a descriptive fault with operator guidance is logged and displayed on the HMI.
- **Safety-Critical Faults (e.g., enclosure door interlock broken, E-Stop pressed, light curtain intrusion):** The safety PLC triggers an immediate and unconditional laser shutdown (≤10 ms response time) and motion stop. The machine transitions to a safe state within 500 ms. Recovery requires clearing the fault condition and a manual reset sequence. A physical administrator key override is required for Class 4 service mode operation with open enclosure panels.
- **Non-Critical Faults (e.g., assist gas pressure low, chiller temperature warning, fume extraction filter clogging):** An alert is generated on the HMI and, if configured, sent as a remote notification (SW Alert). The current cutting cycle may be allowed to complete, but the next cycle initiation is inhibited until the fault is resolved and acknowledged.
- **Power Loss:** A UPS or controlled shutdown capacitor bank ensures the laser optics and motion controller can execute a safe shutdown sequence (retract Z-axis, park gantry, close laser shutter) to prevent damage.
- **Fire Detection:** Smoke and thermal sensors inside the enclosure will trigger an emergency laser shutdown and operator alarm.

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3. External Interfaces

3.1 Communication Interfaces

- **[Optional] Facility WiFi connectivity (IEEE 802.11):** For connection to local network for data export or remote HMI access.

- **[Optional] Internet connectivity:** For secure VPN-based remote diagnostics, monitoring, and dashboard access via IoT gateway.
- **Factory Integration (OPC UA):** An OPC UA server interface shall be provided for integration with customer Manufacturing Execution Systems (MES) or Enterprise Resource Planning (ERP) systems.
- **File Import Formats:** The system shall accept standard industrial file formats including DXF, DWG, STEP, and IGES for part geometry import.

3.2 Mechanical Interfaces

- **Loading Platform Interface:** Defined mechanical and control interface for the automated pallet changer system.
- **Fume Extraction Interface:** Standardized duct connection flange for a downdraft extraction plenum, rated for ≥3000 m³/hr airflow with HEPA and activated carbon filtration.
- **Machine Base & Leveling:** The polymer concrete/mineral cast base shall include leveling pads with a +/- 5mm adjustment range for installation on standard industrial floors (non-isolated).

3.3 Electric Interfaces

- **Main Power Inlet:** High-power, 3-phase 480VAC (380-480VAC, 50/60 Hz), to support the 12kW laser, servo drives, chiller, and ancillaries. System sustained power consumption ≤30 kW; peak ≤45 kW.
- **Power Factor Correction:** The main power supply shall include power factor correction with PF ≥0.95.
- **Auxiliary Power:** 12VDC, 0.5A supply for optical focus control motors.

3.4 Coolant Interface

- **Coolant Inlet:** 3-inch hose inlet for room temperature water at a flow rate of 15 L/min.
- **Coolant Outlet:** 3-inch hose outlet for water up to a temperature of 74°C at a flow rate of 15 L/min.
- **External Chiller:** A dedicated process chiller rated for ≥15 kW cooling capacity is required to maintain laser coolant temperature at 20 +/- 0.5°C.

3.5 GUI Interface

- **Local HMI:** A touchscreen panel (10-15") mounted on the machine for all job setup, manual jogging controls, real-time process visualization (cutting position, laser parameters, sensor feedback, gas pressures), system status dashboard, alarm display with operator guidance, and maintenance functions.
- **Remote GUI:** A web-based dashboard replicating key HMI readouts for remote monitoring via secure network connection. Read-only status display and alarm notification to be supported.

The detailed requirements tables by discipline follow on the next pages.

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4. Laser-Cutting Machine Performance Requirements

Req ID	Requirement	Specification	Source / Verification
1.1	Metal types	The system shall support cutting Aluminum alloys (1xxx-7xxx series).	`sysreq 1.1` / D
1.2	Metal types	The system shall support cutting Austenitic Stainless Steels (304, 316, 316L).	`sysreq 1.2` / D
1.3	Metal plate dimensions	The maximum size of a metal plate shall be 2500mm (length) × 1500mm (width) × 15mm (thickness).	`sysreq 1.3` / I
1.4	Cutting speed	The line speed will be no less than 125m of cut per hour.	`sysreq 1.4` / T
1.5	Machine up-time	Machine up-time shall be >99.5% (i.e., less than ~44 minutes of unscheduled downtime per week).	`sysreq 1.5` / A
1.6	Throughput	The system shall achieve a throughput of 25-50 complete cutting cycles per hour for typical part geometries (250mm characteristic length, mixed thicknesses).	`Claude-SRD SYS-004` / D
1.7	Duty cycle	The system shall be capable of operating continuously for 8-hour shifts with no more than 10 minutes of scheduled maintenance per shift (duty cycle >97%).	`Claude-SRD SYS-006` / D
1.8	MTBF	The system Mean Time Between Failures shall	`Claude-SRD SYS-007` / A

Req ID	Requirement	Specification	Source / Verification
		exceed 2000 hours.	
1.9	Cold-start time	The system shall achieve first-part accuracy (no warm-up cutting required) within 15 minutes of power-on.	`Claude-SRD SYS-014` / T

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5. Laser & Optics Requirements

Req ID	Requirement	Specification	Source / Verification
2.2.1	Cut line resolution / Min feature size	The system shall meet the **Thickness-Dependent Feature Size Specification** in Table 5-A below.	`sysreq 2.2.1` (35µm target), resolved by `Claude-SRD` Table 1.1 / T
2.2.2	Laser source wavelength	The laser wavelength shall be within the range of 1070–1080 nm.	`sysreq 2.2.2` / I
2.2.3	Laser source power	The laser source shall provide output power up to 12 kW, continuously adjustable from 5% to 100% of rated power.	`sysreq 2.2.3`, `Claude-SRD OP-002` / T
2.2.4	Laser source power increments	The laser assembly shall have 2.5% +/- 0.1% power increment capabilities (i.e., [2.5%, 5%, 7.5%, etc.]).	`sysreq 2.2.4` / T
2.2.5	Beam focus range	The laser beam shall have a focus range of 75mm.	`sysreq 2.2.5` / T
2.2.6	Beam DOF	The laser beam DOF shall be 15mm for a resolution of 30 lp/mm at MTF >60%.	`sysreq 2.2.6` / T
2.2.7	Beam shape / Variable BPP	The optics shall support different beam shapes/profiles at the target plane. BPP shall be adjustable from ≤1.0 to ≥8.0 mm·mrad.	`sysreq 2.2.7`, `Claude-SRD OP-001` / T

Req ID	Requirement	Specification	Source / Verification
OP-003	Laser power stability	Laser output power stability shall be +/- 1% of the setpoint over 8 hours of continuous operation.	Claude-SRD OP-003 / T
OP-004	BPP mode switching time	BPP mode switching time shall not exceed 50 ms (10% to 90% beam profile transition).	Claude-SRD OP-004 / T
OP-005	Cutting head zoom	The cutting head shall provide motorized zoom collimation with a focus position adjustment range of +/- 15mm.	Claude-SRD OP-005 / T
OP-006	Focused spot diameter	The focused spot diameter shall be adjustable from 30 µm (fine mode) to 300 µm (power mode) via BPP and collimation control.	Claude-SRD OP-006 / T
OP-007	Coaxial vision	The coaxial vision system shall provide real-time imaging of the cutting zone with ≥5 µm/pixel resolution at the workpiece surface.	Claude-SRD OP-007 / T
OP-008	Coaxial OCT sensor	The coaxial OCT sensor shall measure kerf depth with +/- 20 µm accuracy at a measurement rate of ≥10 kHz.	Claude-SRD OP-008 / T
OP-009	Optics durability	All optical components in the beam path shall withstand full laser power continuously with degradation <1% per 1000 hours.	Claude-SRD OP-009 / T
OP-010	Protective window monitoring	Protective window contamination monitoring shall detect degradation before beam quality degrades	Claude-SRD OP-010 / T

Req ID	Requirement	Specification	Source / Verification
		by 5%.	
OP-012	Nozzle standoff control	Nozzle-to-workpiece standoff distance shall be controllable from 0.3mm to 3.0mm with +/- 0.05mm accuracy via capacitive height sensing.	`Claude-SRD OP-012` / T

Table 5-A: Thickness-Dependent Feature Size Specification *This specification resolves the contradiction between a single flat 35µm requirement and the laws of physics. There is no single existing laser technology that can achieve a 35µm kerf through 15mm material.*

Material Thickness	Minimum Feature Size	Processing Method (BPP Mode)	Rationale
< 0.5 mm	35 µm	Fine BPP (high brightness)	Physics-limited near the diffraction-limited focal spot.
0.5 – 2.0 mm	50 – 80 µm	Fine BPP (high brightness)	Achievable aspect ratio.
2.0 – 6.0 mm	100 – 150 µm	Standard BPP	Kerf limited by beam divergence.
6.0 – 15.0 mm	200 – 350 µm	Power BPP (distributed beam)	Physics-limited kerf width for thick-section cutting.

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6. Laser Safety Requirements

Req ID	Requirement	Specification	Source / Verification
2.2.8	Laser safety classification (closed)	With all enclosure covers closed, the machine shall be categorized as Laser Class 1.	`sysreq 2.2.8` / T
2.2.9	Laser safety classification (service area access)	With covers open for the general service area (but laser/optics service areas still closed), the machine shall remain Laser Class 1.	`sysreq 2.2.9` / T
2.2.10	Laser safety classification (laser/optics service	With covers open for the laser and optics service areas as well as	`sysreq 2.2.10` / T

Req ID	Requirement	Specification	Source / Verification
	area access)	the target internal service area, the machine shall be categorized as Laser Class 4.	
5.1.1	Laser safety interlocks	The machine covers for laser, optics, and internal target service areas shall have safety interlocks to shut down the laser in case of unauthorized opening. A physical administrator key override shall be provided.	`sysreq 5.1.1` / T
SA-001	Laser product standard	The system shall be classified as a Class 1 laser product per IEC 60825-1 when all enclosure panels are in place.	`Claude-SRD SA-001` / T
SA-002	Laser shutdown response time	All safety interlocks shall disable the laser within 10 ms of access door opening.	`Claude-SRD SA-002` / T
SA-003	Safety integrity level	The safety system (laser shutdown function) shall achieve SIL-2 per EN 62061 (or PL d, Cat. 3 per EN ISO 13849-1).	`Claude-SRD SA-003`, `ChatGPT-Phase1` / A
SA-004	Emergency stop	Emergency stop buttons shall be accessible from all operator positions. Activation shall bring the machine to a safe state within 500 ms.	`Claude-SRD SA-004` / T
SA-005	Enclosure attenuation	The laser enclosure shall attenuate laser radiation to below the Maximum Permissible Exposure (MPE) at all external surfaces. Attenuation shall be rated at OD ≥7 for 1 µm wavelength.	`Claude-SRD SA-005`, `ChatGPT-Phase1` / T

Req ID	Requirement	Specification	Source / Verification
SA-007	Fire detection	The system shall include fire detection (smoke/thermal sensor) inside the enclosure with automatic laser shutdown and operator alarm.	`Claude-SRD SA-007` / D
SA-008	Gas safety	The gas delivery system shall include leak detection, overpressure relief valves, and automatic shutoff on fault detection.	`Claude-SRD SA-008` / T
SA-009	Noise emission	Noise emission shall not exceed 80 dB(A) at 1 meter from the enclosure during normal cutting operations.	`Claude-SRD SA-009` / T

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7. Mechanical Requirements

Req ID	Requirement	Specification	Source / Verification
2.1.2	Machine dimensions	Machine width shall be 950mm. Machine height shall be 1950mm. Machine length is TBD.	`sysreq 2.1.2` / I
SYS-013	Total system footprint	The total system footprint, including all ancillaries (chiller, extraction, electrical cabinet), shall not exceed 6000mm × 4000mm.	`Claude-SRD SYS-013` / I
2.4.1	Batch height	Batch maximum height for 25 plates including spacers shall be 495mm. Minimum single-plate batch height is 0.5mm.	`sysreq 2.4.1` / I
2.4.2	Auto plate loading	The plates shall be loaded one-by-one from the plate platform	`sysreq 2.4.2` / D

Req ID	Requirement	Specification	Source / Verification
		to the machine automatically.	
ME-001	Gantry positioning accuracy	The gantry shall provide positioning accuracy of +/- 10 µm over the full 2500 mm × 1500 mm work area.	Claude-SRD ME-001 / T
ME-002	Gantry repeatability	Gantry bidirectional repeatability shall be +/- 5 µm over the full work area.	Claude-SRD ME-002 / T
ME-003	Maximum traverse speed	Maximum gantry traverse speed shall be ≥100 m/min on both X and Y axes.	Claude-SRD ME-003 / T
ME-004	Gantry acceleration	Gantry acceleration shall be ≥1.0 G (9.8 m/s²) on both X and Y axes.	Claude-SRD ME-004 / T
ME-005	Machine base material & natural frequency	The machine base shall be manufactured from polymer concrete or mineral casting with a first mode natural frequency ≥80 Hz (unloaded).	Claude-SRD ME-005 / T, A
ME-006	Thermal drift	Thermal drift of the gantry shall not exceed 5 µm/°C across the full work area. A minimum of 6 temperature sensors shall be embedded in the structure for thermal compensation.	Claude-SRD ME-006 / T
ME-007	Work table load capacity	The work table shall support a maximum workpiece mass of 500 kg (full 2500×1500×15mm stainless steel sheet ~450 kg) with deflection ≤0.1 mm.	Claude-SRD ME-007 / A, T
ME-008	Z-axis specifications	The Z-axis (focus) shall provide +/- 5 mm travel with positioning resolution of 1 µm and	Claude-SRD ME-008 / T

Req ID	Requirement	Specification	Source / Verification
		bandwidth ≥100 Hz.	
ME-009	Direct drive axes	All linear axes (X, Y) shall use direct-drive ironless linear motors to eliminate mechanical backlash.	`Claude-SRD ME-009` / I
ME-010	Moving mass	The gantry moving mass (head carriage + cutting head + Z-axis assembly) shall not exceed 25 kg.	`Claude-SRD ME-010` / I
ME-011	Vibration at nozzle	Vibration amplitude at the cutting nozzle tip shall not exceed 2 µm RMS during cutting motion at 10 m/min.	`Claude-SRD ME-011` / T
ME-012	Sheet exchange time	The work table shall accommodate automated sheet exchange (shuttle table or similar mechanism) with exchange time ≤60 seconds.	`Claude-SRD ME-012` / T
ME-014	Slat replacement time	Cutting table slats/supports shall be replaceable without tools, with individual slat replacement time ≤30 seconds.	`Claude-SRD ME-014` / D

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8. Electronics & HW Requirements

Req ID	Requirement	Specification	Source / Verification
2.5.1	Laser source power supply	The laser source power input shall be 480VAC to support 12kW output power.	`sysreq 2.5.1` / I
2.5.2	Optics focus motors power supply	The motors power supply for optical focus control shall be 12VDC, 0.5A.	`sysreq 2.5.2` / I
4.3.1	Main power inlet	The system's main power inlet shall be high-power 480VAC,	`sysreq 4.3.1` / I

Req ID	Requirement	Specification	Source / Verification
		3-phase, 50/60 Hz.	
EL-001	CNC servo update rate	The CNC controller shall execute motion interpolation at ≥4 kHz servo update rate with sub-microsecond jitter.	`Claude-SRD EL-001` / T
EL-002	Encoder resolution	All motion axes shall use absolute linear encoders with resolution ≤0.1 µm. (e.g., Heidenhain LIC, Renishaw RESOLUTE).	`Claude-SRD EL-002`, `ChatGPT-Phase1` / I, T
EL-003	EtherCAT cycle time	The servo drives shall support EtherCAT communication with a cycle time ≤250 µs.	`Claude-SRD EL-003` / T
EL-004	Electrical cabinet thermal management	The electrical cabinet shall maintain component temperatures within rated operating ranges with ambient temperatures up to 40°C.	`Claude-SRD EL-004` / T
EL-005	Sensor sampling rate & resolution	All sensor analog inputs (photodiode, pyrometer, acoustic emission) shall be sampled at ≥100 kHz with ≥16-bit resolution.	`Claude-SRD EL-005` / T
EL-006	Laser interface command latency	The laser interface (digital, e.g., SPI or EtherCAT) shall have a power command latency ≤1 ms.	`Claude-SRD EL-006` / T
EL-007	UPS / controlled shutdown	The system shall include a UPS or controlled shutdown energy storage capacity to safely shutter the laser, retract the Z-axis, and park the gantry in the event of power loss.	`Claude-SRD EL-007` / D
EL-008	EMC emissions	EMC emissions shall comply with EN 55011 Group 2, Class A	`Claude-SRD EL-008` / T

Req ID	Requirement	Specification	Source / Verification
		(industrial environment).	
EL-009	EMC immunity	EMC immunity shall comply with EN 61000-6-2 (immunity for industrial environments).	`Claude-SRD EL-009` / T
EL-010	Safety I/O diagnostic coverage	All safety-critical I/O (E-stop, interlocks, light curtains, laser enable) shall be routed through the safety PLC with diagnostic coverage ≥99%.	`Claude-SRD EL-010` / A, T
EL-011	Gas pressure sensor feedback	Assist gas pressure sensors shall provide feedback with an accuracy of +/- 0.1 bar at measurement rates ≥100 Hz.	`Claude-SRD EL-011` / T
EL-012	Main power power factor	The main power supply shall have Power Factor Correction (PFC) with PF ≥0.95.	`Claude-SRD EL-012` / T

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9. Control & Feedback Requirements

Req ID	Requirement	Specification	Source / Verification
2.6.1.1	Power measurement	The laser power measurement will be via a laser power meter split off from the main beam.	`sysreq 2.6.1.1` / I
2.6.1.2	Power measurement accuracy	The power measurement shall be accurate to within +/- 0.5% of the real beam power (as verified by an Ophir Optronics power meter or equivalent reference).	`sysreq 2.6.1.2` / T
2.6.1.3	Power increments (control)	The power control shall support 2.5% +/- 0.1% power increments or	`sysreq 2.6.1.3` / T

Req ID	Requirement	Specification	Source / Verification
		better.	
2.6.2	Cooling Control & Feedback	Active control and monitoring of coolant temperature, flow rate, and fault status for both laser and sample cooling circuits.	`sysreq 2.6.2` / T
SW-001	Adaptive cutting control loop rate	The real-time control software shall execute the multi-sensor adaptive cutting control loop at ≥4 kHz update rate. Parameters adjusted: laser power, cutting speed, gas pressure, and focus position.	`Claude-SRD SW-001` / T
SW-006	Auto BPP mode selection	The software shall implement automatic BPP mode selection based on part geometry analysis (feature size detection in CAM).	`Claude-SRD SW-006` / D
SW-011	Auto nozzle centering	The software shall implement automatic nozzle centering calibration using the coaxial vision system.	`Claude-SRD SW-011` / D
3.2.1	Power auto-calibration	The laser power will auto-calibrate periodically for power verification.	`sysreq 3.2.1` / D
3.2.2	Motors auto-calibration	The motors shall have an auto-calibration and homing procedure to run periodically, including accuracy verification against a reference artifact.	`sysreq 3.2.2` / D

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10. Cooling & Thermal Management Requirements

Req ID	Requirement	Specification	Source / Verification
2.2.11.1	Laser active cooling	The laser system shall	`sysreq 2.2.11.1` /

Req ID	Requirement	Specification	Source / Verification
		have an active cooling system to support eviction of residual heat from power consumption (waste heat ~8-12 kW).	I
2.2.11.2	Laser coolant type	The liquid coolant for the laser cooling shall be room temperature water.	`sysreq 2.2.11.2` / I
2.3.2.1	Sample active cooling	The sample/workpiece shall have active cooling.	`sysreq 2.3.2.1` / I
2.3.2.2	Sample coolant type	The liquid coolant for the sample cooling shall be room temperature water.	`sysreq 2.3.2.2` / I
4.4.1	Coolant inlet specification	The coolant inlet shall be a 3-inch hose inlet of room temperature water at a flow rate of 15 L/min.	`sysreq 4.4.1` / I
4.4.2	Coolant outlet specification	The coolant outlet shall be a 3-inch hose outlet of water up to a temperature of 74°C at a flow rate of 15 L/min.	`sysreq 4.4.2` / I
PR-005	Chiller temperature stability	The system chiller shall maintain laser coolant temperature at 20 +/- 0.5°C with a cooling capacity ≥15 kW.	`Claude-SRD PR-005` / T
PR-006	Compressed air quality	Compressed air supply (for pneumatic actuators, air knife/optics purge) shall be clean dry air per ISO 8573-1 Class 1.4.1.	`Claude-SRD PR-006` / I

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11. Software Features & User Interface Requirements

Req ID	Requirement	Specification	Source / Verification
6.1	SW alerts	The system shall	`sysreq 6.1`,

Req ID	Requirement	Specification	Source / Verification
		provide operator alerts for all fault conditions, consumable wear status, predictive maintenance indicators, and scheduled maintenance requirements. Alerts shall be displayed on the HMI and capable of remote notification.	Claude-SRD SYS-012 / D
SW-002	File format support	The system shall accept standard industrial file formats for part geometry import: DXF, DWG, STEP, IGES.	Claude-SRD SW-002 / D
SW-003	Nesting material utilization	The CAM/nesting module shall automatically generate optimized nesting layouts with material utilization ≥85% for typical mixed-part jobs.	Claude-SRD SW-003 / D
SW-004	Real-time HMI dashboard	The HMI shall provide real-time visualization of: cutting position, laser parameters (power, BPP mode), sensor feedback (OCT depth, temperatures), gas pressures, system status, and active alarm conditions.	Claude-SRD SW-004 / D
SW-005	Process data logging	The system shall log all process parameters and sensor data at ≥	