System & Optics
Doc # 000-001

LASER-CUTTING MACHINE SYSTEM REQUIREMENTS

Consolidated & Reconciled Document

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Revision History

Rev	Date	Author	Description
1.0	2026-Apr-15	Asaf Granot	Initial Version (sysreq_example baseline)
1.1	2026-May-15	Asaf Granot	Initial top-level requirements
2.0	2026-May-06	Systems Eng.	Consolidated SRD: merged sysreq_example (primary), Claude-SRD Rev A, and supplementary analysis; contradictions resolved per document priority order

Related Documents

Doc #	Title	Notes
000-000	Laser-Cutting Machine Product Requirements	Parent document
000-001	Laser-Cutting Machine Sysreq Ver 1.1	Primary source (highest priority)
000-002	System Design & Architecture Rev A, Feb 2026	Secondary source
000-003	Phase 1 Laser-Cutting Machine Design Analysis (supplementary)	Tertiary / reference only

Acronyms and Terms

Term / Acronym	Definition
AE	Acoustic Emission
BOM	Bill of Materials
BPP	Beam Parameter Product
CAM	Computer-Aided Manufacturing
CNC	Computer Numerical Control
CW	Continuous Wave
DOF	Depth of Field
EMC	Electromagnetic Compatibility
HEPA	High-Efficiency Particulate Air
HMI	Human-Machine Interface
MES	Manufacturing Execution System

MTBF	Mean Time Between Failures
MTF	Modulation Transfer Function
OCT	Optical Coherence Tomography
OEL	Occupational Exposure Limit
PFC	Power Factor Correction
PLC	Programmable Logic Controller
SIL	Safety Integrity Level
TBD	To Be Determined
UPS	Uninterruptible Power Supply
VPN	Virtual Private Network

Background

This document defines the top-level system requirements for a laser-cutting machine for metal processing, developed by System and Optics. The machine shall cut Aluminum and Stainless-steel accurately and shall be integrated into a production line with loading and unloading platforms.

This is the first laser-cutting product of System and Optics. It shall leverage existing machine-vision solutions from Product-A and Product-B as feedback and control modules. The system comprises the following modules: Laser & Optics; Control & Feedback; Computing & Calculations; Electronics & HW; Plate Loading Mechanics; and Sample Mechanics.

Document priority for contradiction resolution (descending): (1) sysreq_example Ver 1.1 [Doc 000-001], (2) Claude-SRD Rev A [Doc 000-002], (3) supplementary analysis [Doc 000-003]. All requirements are traced to their source in the Requirement Tracking Table.

Top-Level System Block Diagram

The following table represents the top-level functional block diagram of the laser-cutting machine, showing all major subsystems and their groupings. Signal / data flows are described in Section 3.

CONTROL & FEEDBACK • Plate Identification • Beam Intensity Monitor • Plate Placement • Cut Progress • Beam Shape • Laser Cooling • Beam Location • Sample Cooling	**LASER + OPTICS MODULE** • Laser Source (IPG / Coherent / Raycus) • Variable-BPP Control • Power Supply | Laser Cooling • Beam Shaping Optics • – Shape | Focus | Movement • Cutting Head (Precitec ProCutter 2.0) • Coaxial OCT | Coaxial Camera • Capacitive Height Sensing	**ELECTRONICS & HW** • Computing (Industrial PC) • CNC Controller (Beckhoff TwinCAT) • EtherCAT Servo Drives • Safety PLC (Pilz PNOZmulti 2) • Power Handling | PDU • Sensor Interfaces • I/O Modules (~200 I/O pts)
PLATE LOAD MECHANICS • Plate Rack (up to 25 plates) • Plate Pick & Place Mechanics • Auto-Feed to Cutting Table • Plate Rack Removal • Plate Unload / Output Staging	**SAMPLE MECHANICS** • Sample Holder + XYZ Gantry • Linear Motor Drives (X, Y, Z) • Polymer Concrete Base • Ready Part Mechanics • Debris Removal → Debris Bin • Plate / Sample Cooling • Slat Work Table (replaceable)	**COMPUTING & CALCULATIONS** • Auto-Calibrations • Coolant Flow Control • Laser Intensity Control • Laser Focus Control • Motors' Movement Planning • Cut Trajectory / CAM / Nesting • Remote Support • Parts Handling Logic • Auto-Updates • Facility Interface & Control
GAS DELIVERY • N_2 supply (≤ 25 bar) • O_2 supply [optional, ≤ 6 bar] • Proportional Control Valves • Pressure Sensors & Interlocks	**FACILITY COOLANT / SERVICES** • Coolant Inlet: 3" hose, 15 L/min • Coolant Outlet: ≤74°C, 15 L/min • Compressed Air (ISO 8573-1 Cl.1.4.1) • Fume Extraction (≥3000 m³/hr HEPA)	**EXTERNAL INTERFACES** • [Opt.] Facility WiFi • [Opt.] Internet / Remote Support • OPC UA → MES / ERP • 480 VAC 3-phase Power Inlet • HMI Touchscreen (operator) • Remote Monitoring Dashboard

Executive Summary

This document presents the complete system-level requirements for an industrial laser-cutting machine targeting the metal processing industry. The system shall process Aluminum and Stainless-steel sheets up to 2500 × 1500 mm, with thicknesses from foil (sub-0.1 mm) to 15 mm plate, achieving a minimum cutting feature of 35 µm (at thickness < 0.5 mm), at a production throughput of 25–50 parts per hour, within a target BOM cost of $150,000 USD.

Three candidate architectures were evaluated. Architecture C — Variable-BPP Fiber Laser with High-Precision Gantry — is the recommended leading architecture. It provides the best achievable feature sizes within physics limits using a single laser source, incorporates advanced multi-sensor process monitoring, and is manufacturable within the budget envelope. Architecture B (Dual-Source Hybrid with ultrafast laser) would be required only if the 35 µm requirement must be met at thicknesses above 0.5 mm, but at 2–3× the budget and very high development risk.

> **NOTE:** CRITICAL FEASIBILITY FINDING: The combination of a 35 µm minimum feature size across the full 15 mm thickness range represents a fundamental physics conflict that cannot be resolved by any single existing laser cutting technology. A thickness-dependent feature-size specification is adopted (Table 1.1 in Section 1). Product management must formally accept this before PDR.

System Architecture Analysis

This section summarises the three candidate architectures, provides a full engineering comparison, and states the architecture recommendation with rationale. All architecture descriptions are drawn from Doc 000-002 (Claude-SRD Rev A).

Architecture A — Conventional High-Power CW Fiber Laser

This is the industry-standard approach used by Trumpf TruLaser, Bystronic ByStar, and Mazak Optiplex. A single high-power continuous-wave (CW) fiber laser (6–8 kW) drives a flying-optics gantry. The laser source is stationary; the beam is delivered via fiber to a cutting head that traverses in X-Y over the stationary workpiece. Z-axis focus control and capacitive height sensing regulate standoff distance.

Strengths: Mature technology, proven supply chain, lowest unit cost, highest thick-material cutting speed, well-understood maintenance profile.

Limitations: Cannot achieve 35 µm features at any thickness (minimum on thin stock ≈ 80–100 µm). No beam adaptability; limited process flexibility.

BOM estimate: $100–130 K. Budget-compliant but leaves no margin for precision upgrades.

Architecture B — Dual-Source Hybrid (CW Fiber + Ultrafast Laser)

This architecture combines a medium-power CW fiber laser (4–6 kW) for bulk cutting with an ultrafast pulsed laser (picosecond, 50–100 W average power, e.g. Trumpf TruMicro 5000 or Coherent Monaco) for micro-feature cutting on thinner stock. Both sources share a common high-precision gantry with automatic head switching.

Strengths: Can achieve ~30–40 µm features on thin material (sub-0.5 mm) via cold ablation; excellent edge quality; genuinely capable of both bulk cutting and micromachining.

Limitations: Ultrafast source alone costs $100–200 K, far exceeding the total BOM budget. System complexity doubles. Ultrafast still cannot achieve 35 µm at 15 mm. MTBF of ultrafast source ≈ 20–40 K hrs vs. >100 K hrs for CW. Development risk very high.

BOM estimate: $250–350 K. Fails budget constraint by 2–3×.

Architecture C — Variable-BPP Fiber Laser with High-Precision Gantry (RECOMMENDED)

This architecture leverages variable Beam Parameter Product (BPP) fiber laser technology (IPG AMB series, Coherent HighLight FL-ARM, or nLIGHT with adjustable ring/core beam). The laser dynamically adjusts beam profile between a tight, high-brightness mode (for thin material and fine features) and a wider, distributed mode (for stable thick-section cutting). This is combined with a polymer concrete gantry base, ironless linear motor drives, and an advanced cutting head with motorized zoom collimation, coaxial OCT, and a multi-sensor adaptive control loop.

Strengths: Single laser source; best achievable feature sizes within physics limits (~50–80 µm on thin stock); single-source reliability (>100 K hrs MTBF); full adaptive process control; BOM tight but achievable; modular platform for future upgrades.

Limitations: Cannot achieve 35 µm at any thickness (physics-limited to ~50 µm minimum with CW). Variable-BPP technology is newer — vendor selection is more limited than conventional CW. Requires sophisticated real-time BPP mode-switching software.

BOM estimate: $134–165 K. Achievable at $150–165 K target with mid-range laser source and Raytools head for production units.

Architecture Comparison Table

Table A.1 — Full engineering comparison across all three candidate architectures. Architecture C values are the basis for the requirements in this document.

Parameter	Arch A: Conventional CW Fiber	Arch B: Dual-Source Hybrid	Arch C: Variable-BPP (RECOMMENDED)
LASER SOURCE			
Laser type	6–8 kW CW fiber (IPG YLS / Raycus)	4–6 kW CW + 50–100 W ultrafast (ps/fs)	6–8 kW variable-BPP fiber (IPG AMB / Coherent ARM)
BPP	Fixed, 2–4 mm·mrad	CW: 2–4 / UF: <0.4 mm·mrad	Adjustable 0.8–8 mm·mrad
Wall-plug efficiency	~40–45%	CW: ~40% / UF: ~15–20%	~38–42%
CUTTING CAPABILITY			
Min feature (t < 0.5 mm)	~80–100 µm	~30–40 µm (ultrafast)	**~50–80 µm**
Min feature (t = 15 mm)	~300–400 µm	~200–300 µm (CW only)	~200–350 µm
Max cut speed (1 mm SS)	30–50 m/min	CW: 25–40 / UF: 0.5 m/min	30–50 m/min
Max cut speed (15 mm SS)	1.0–1.5 m/min	0.8–1.2 m/min (less CW pwr)	1.0–1.5 m/min
Throughput	30–50 parts/hr	15–30 (head-switch overhead)	**25–45 parts/hr**
MOTION SYSTEM			
Gantry type	Steel weldment, belt/rack	Granite/polymer concrete, linear motor	Polymer concrete, linear motor
Positioning accuracy	±15–25 µm	±3–5 µm	**±5–10 µm**
Repeatability	±10 µm	±1–2 µm	±3–5 µm
Max traverse speed	100–140 m/min	60–80 m/min	80–120 m/min
Acceleration	1.0–1.5 G	0.8–1.2 G	1.0–1.5 G
CONTROL & FEEDBACK			
CNC platform	Siemens / Beckhoff / Fanuc	Custom ACS / Beckhoff hybrid	Beckhoff TwinCAT / ACS SPiiPlus
Process feedback	Basic (pierce detect)	Advanced (OCT, camera, AE)	Advanced (OCT, camera, AE)
Adaptive control	Limited (height only)	Full (dual-source coord.)	Full (BPP + speed + gas + focus)
Real-time loop rate	1–4 kHz	10–50 kHz	4–10 kHz
OPTICS			
Cutting head	Standard autofocus	Dual heads: CW +	Adaptive zoom + autofocus

	(Precitec / Raytools)	galvo	(Precitec ProCutter 2.0)
Focus range	Fixed collimation	CW: fixed / UF: scanner	Motorized collimation zoom ±15 mm
Coaxial vision	Optional	Yes (both heads)	Integrated OCT + camera
Nozzle type	Standard conical	CW: conical / UF: none	Conical + micro-nozzle option
SAFETY & ENCLOSURE			
Laser safety class	Class 1 (enclosed)	Class 1 (enclosed)	Class 1 (enclosed) / Class 4 (service)
Safety PLC	SIL-2 (Pilz / Sick)	SIL-2 (Pilz / Sick)	SIL-2 (Pilz PNOZmulti 2)
Fume extraction	Standard HEPA	Standard + ultrafast debris handling	Segmented downdraft, HEPA + carbon
Enclosure complexity	Low	High (dual beam paths)	Medium
GAS DELIVERY			
Assist gas types	N_2, O_2	N_2, O_2 + process gas for UF	N_2 (≤25 bar), O_2 (≤6 bar)
Max pressure	20 bar N_2	20 bar N_2	25 bar N_2
Flow control	Manual regulator	Proportional electronic	Proportional electronic, closed-loop
COST & RISK			
Estimated BOM	$100–130 K	$250–350 K	**$134–165 K**
Budget compliance	PASS	FAIL (>2× over budget)	**MARGINAL — achievable with optimisation**
Development risk	Low	Very High	Medium
Time to prototype	6–9 months	18–24 months	10–14 months
Supply chain risk	Low (mature vendors)	High (ultrafast sources limited)	Medium (BPP laser is newer but available)
MAINTENANCE			
Laser MTBF	>100,000 hrs	CW: >100 K / UF: ~20–40 K hrs	>100,000 hrs
Consumables	Nozzles, lenses, gas	Double consumable set	Nozzles, lenses, gas
Service complexity	Low	Very High	Medium
SCALABILITY			
Upgrade path	Limited to laser power only	Full but extremely costly	BPP range, power, head options — modular platform
Platform reuse	Standard frames	Custom platform (not reusable)	Modular platform — supports future laser upgrades

Architecture Recommendation

Architecture C (Variable-BPP Fiber Laser with High-Precision Gantry) is selected as the leading architecture for the following reasons:

1. Best balance of feature-size capability vs. cost: achieves 50–80 µm on thin stock — closest feasible to the 35 µm requirement — without exceeding the BOM budget.
2. Single laser source eliminates the complexity, cost, and reliability penalties of Architecture B's dual-source approach.

3. Variable BPP provides genuine process flexibility: thick-section cutting with distributed beam, fine-feature cutting with concentrated beam — same source.
4. Advanced process monitoring (OCT, coaxial camera, acoustic emission) enables adaptive quality control that partially compensates for the gap between achievable and target feature sizes.
5. Moderate development risk with a clear path to serial production within 10–14 months.
6. Modular platform: future laser source improvements in BPP technology directly improve feature size without mechanical redesign.

Risk note: Architecture C does NOT meet the 35 µm feature requirement at any thickness with CW cutting physics. If 35 µm is non-negotiable, Architecture B is the only candidate, but it will exceed BOM by at least 2× and carries very high development risk. A requirement revision is strongly recommended.

1. Performance Requirements

PERF-001 Metal types: the system shall support cutting Aluminum alloys (1xxx–7xxx series). — Verification method: Demonstration.

PERF-002 Metal types: the system shall support cutting austenitic Stainless-steel grades 304, 316, and 316L.

PERF-003 Metal plate dimensions: the maximum workpiece size shall be 2500 mm (length) × 1500 mm (width) × 15 mm (thickness). — Verification method: Inspection.

PERF-004 Cutting speed: the line cut speed shall be no less than 125 m of cuts per hour under nominal operating conditions. — Verification method: Test.

PERF-005 Part throughput: the system shall complete 25 to 50 full cutting cycles per hour for typical part geometries with a 250 mm characteristic dimension and mixed thickness distribution. — Verification method: Demonstration.

PERF-006 Machine up-time: machine operational availability shall exceed 99.5%, equivalent to no more than 1 hour of unplanned downtime per week. [Demonstration]

Table 1.1 — Thickness-Dependent Minimum Feature Size Specification

Material Thickness	Min. Feature Size	Processing Method	Rationale
< 0.5 mm	≤ 35 µm	Ultrafast laser (ps/fs) or tight-focus CW	Physics-achievable; primary 35 µm target
0.5 – 2.0 mm	≤ 80 µm	Ultrafast or tight-focus CW	Moderate aspect ratio
2.0 – 6.0 mm	≤ 150 µm	CW fiber laser, fine BPP mode	Beam propagation limited
6.0 – 15.0 mm	≤ 350 µm	CW fiber laser, power mode	Physics-limited kerf width

NOTE: Table 1.1 reflects physics constraints confirmed in Doc 000-002. The 35 µm requirement at thickness < 0.5 mm is the primary specification per Doc 000-001. Requirements for thicker material are derived from beam physics. Product management sign-off is required before PDR.

2. System Architecture Requirements

2.1 General

ARCH-001 Maximum BOM cost: the system BOM shall not exceed $150,000 USD (target). An absolute ceiling of $165,000 USD applies at initial production volumes.

ARCH-002 Machine housing dimensions: the machine cabinet shall not exceed 95 cm width and 195 cm height; length is TBD. Total system footprint including all ancillaries shall not exceed 6000 mm × 4000 mm. — Verification method: Inspection.

ARCH-003 Plate batch size: the system shall support a raw-material batch of up to 25 plates. — Verification method: Demonstration.

ARCH-004 System architecture: the leading architecture shall be a Variable-BPP Fiber Laser with High-Precision Gantry (Architecture C). The laser source shall provide dynamically adjustable BPP to support both fine-feature and bulk-cutting modes from a single source. — Verification method: Inspection, Analysis.

ARCH-005 The system shall be designed for serial production of a minimum of 10 units per year. — Verification method: Analysis.

ARCH-006 MTBF: the system MTBF shall exceed 2000 hours of operation. — Verification method: Analysis.

ARCH-007 Cold-start readiness: the system shall be ready for production cutting within 15 minutes of power-on. — Verification method: Test.

ARCH-008 Total electrical power consumption shall not exceed 30 kW sustained and 45 kW peak. — Verification method: Test.

ARCH-009 The system shall operate in a factory environment of 18–28°C ambient temperature and relative humidity below 80%, non-condensing. [Analysis]

2.2 Laser and Optics

LO-001 Cut line resolution: the optical system shall achieve a cut line resolution below 17.5 μm in order to support the 35 μm minimum feature size. — Verification method: Test.

LO-002 Laser source wavelength: the laser wavelength shall be in the range 1070–1080 nm. — Verification method: Test.

LO-003 Laser source power: the laser source shall provide output power up to 12 kW. Working power range for variable-BPP operation is nominally 6–8 kW. — Verification method: Test.

LO-004 Laser source power increments: the laser assembly shall provide power adjustment in increments of 2.5% ± 0.1%. — Verification method: Test.

LO-005 Laser output power stability: power shall be stable to ±0.5% of set-point over 8 hours of continuous operation. — Verification method: Test.

LO-006 Beam focus: the laser optical assembly shall provide a focal length of 75 mm. — Verification method: Test.

LO-007 Beam Depth of Field: the DOF shall be ≥ 15 mm for a resolution of 30 lp/mm at MTF > 60%. — Verification method: Test.

LO-008 Beam shape: the optics shall support variable beam shape via BPP adjustment (range: 0.8–8.0 mm·mrad, adjustable). BPP mode switching time shall not exceed 50 ms. — Verification method: Test.

LO-009 Focused spot diameter shall be adjustable from ≤ 35 μm (fine mode) to 300 μm (power mode) via combined BPP and collimation control. — Verification method: Test.

LO-010 Motorized focus adjustment: the cutting head shall provide motorized zoom collimation with ±15 mm range and ±5 μm accuracy. — Verification method: Test.

LO-011 Coaxial vision: the cutting head shall include an integrated coaxial vision sensor with ≥ 5 μm/pixel resolution at the workpiece. — Verification method: Test.

LO-012 Nozzle standoff distance shall be controllable from 0.3 mm to 3.0 mm with ±0.05 mm accuracy via capacitive height sensing. — Verification method: Test.

LO-013 Protective window monitoring shall raise an alarm before beam-quality degradation exceeds 5%. — Verification method: Demonstration.

LO-014 Laser safety – closed covers: with all protective covers closed, the machine shall be classified Laser Class 1 per IEC 60825-1. [Test]

LO-015 Laser safety – service covers open (laser/optics or target internal service area): the machine shall be classified Laser Class 4. Access shall require a physical administrator key override. — Verification method: Inspection, Demonstration.

LO-016 Active laser cooling: the laser system shall incorporate active liquid cooling. The chiller shall maintain coolant temperature at 20 ± 0.5°C with cooling capacity ≥ 15 kW. — Verification method: Test.

LO-017 Laser cooling coolant: the liquid coolant shall be clean water at room temperature on the facility supply side (see IF-005, IF-006). — Verification method: Inspection.

LO-018 All optical components in the beam path shall withstand full rated laser power continuously with degradation < 1% per 1000 hours. — Verification method: Test.

2.3 Sample Mechanics

ME-001 Sample movement (XYZ): the gantry shall provide positioning accuracy of ±10 μm over the full 2500 × 1500 mm work area, and bidirectional repeatability of ±5 μm. [Test]

ME-002 Maximum gantry traverse speed: ≥ 100 m/min on both X and Y axes. — Verification method: Test.

ME-003 Gantry acceleration: ≥ 1.0 G (9.8 m/s²) on both X and Y axes. — Verification method: Test.

ME-004 All linear axes shall use direct-drive linear motors with zero mechanical transmission backlash. — Verification method: Inspection.

ME-005 Gantry thermal drift shall not exceed 5 µm/°C across the full work area. — Verification method: Test.

ME-006 The machine base shall be manufactured from polymer concrete or mineral cast with first structural resonance ≥ 80 Hz (unloaded). — Verification method: Test, Analysis.

ME-007 The Z-axis (focus) shall provide ±5 mm travel, 1 µm positioning resolution, and ≥ 100 Hz closed-loop bandwidth.

ME-008 The gantry moving mass (head carriage + cutting head + Z-axis) shall not exceed 25 kg. — Verification method: Inspection.

ME-009 Vibration at the cutting nozzle tip shall not exceed 2 µm RMS during cutting motion at 10 m/min. — Verification method: Test.

ME-010 Sample active cooling: the workpiece support area shall have active cooling provisions to manage thermal loading. — Verification method: Demonstration.

ME-011 Sample cooling coolant: the liquid coolant for sample/table cooling shall be clean water at room temperature on the facility supply side. — Verification method: Inspection.

2.4 Plate Loading Mechanics

PL-001 Batch height: the plate rack maximum height shall be 495 mm; minimum single-plate height is 0.5 mm. — Verification method: Inspection.

PL-002 Auto plate loading: plates shall be loaded one-by-one from the plate platform to the machine cutting position automatically. — Verification method: Demonstration.

PL-003 Work table exchange time: the automated sheet exchange (shuttle table or equivalent) shall complete within 60 seconds. — Verification method: Test.

PL-004 Waste slag and cut parts shall be collected in accessible drawers or bins removable without entering the cutting zone. — Verification method: Inspection.

2.5 Electronics and Hardware

EL-001 Laser source power supply: the laser source power inlet shall be 480 VAC 3-phase to support up to 12 kW laser output. — Verification method: Inspection.

EL-002 Optics focus motors: the motor power supply for optical focus control shall be 12 VDC at 0.5 A. — Verification method: Inspection.

EL-003 CNC servo update rate: the motion controller shall execute interpolation at ≥ 4 kHz with sub-microsecond jitter. — Verification method: Test.

EL-004 Linear encoder resolution: all motion axes shall use absolute encoders with resolution ≤ 0.1 µm. — Verification method: Inspection, Test.

EL-005 Servo drive communication: drives shall support EtherCAT with cycle time ≤ 250 µs. — Verification method: Test.

EL-006 Sensor sampling: all analog sensor inputs (photodiode, pyrometer, acoustic emission) shall be sampled at ≥ 100 kHz with ≥ 16-bit resolution. — Verification method: Test.

EL-007 The system shall include UPS or controlled shutdown to protect laser optics and motion axes on power loss. — Verification method: Demonstration.

EL-008 EMC emissions shall comply with EN 55011 Group 2 Class A. — Verification method: Test.

EL-009 EMC immunity shall comply with EN 61000-6-2 (industrial environment). — Verification method: Test.

EL-010 Safety-critical I/O (E-stop, door interlocks, light curtains, laser enable) shall be routed through a dedicated safety PLC achieving SIL-2 per EN 62061, with diagnostic coverage ≥ 99%. [Test, Analysis]

EL-011 Main power factor correction: PFC ≥ 0.95. — Verification method: Test.

EL-012 Electrical enclosure protection rating: IP54 minimum. — Verification method: Inspection.

2.6 Control and Feedback

2.6.1 Power Control and Feedback

CF-001 Power measurement: laser power shall be measured via a calibrated split-off from the main beam. — Verification method: Inspection.

CF-002 Power measurement accuracy: the measurement shall be accurate to ±0.5% of actual beam power. Calibration reference shall be an Ophir Optronics power meter or traceable equivalent. — Verification method: Test.

CF-003 Power control increments: the control loop shall support increments of 2.5% ± 0.1% or finer. — Verification method: Test.

CF-004 Real-time adaptive control: the system shall implement a closed-loop adaptive cutting control loop at ≥ 4 kHz, fusing OCT kerf depth, photodiode backscatter, pyrometer temperature, acoustic emission, and coaxial camera to adjust laser power, speed, gas pressure, and focus in real-time. — Verification method: Test.

2.6.2 Cooling Control and Feedback

CF-005 Laser chiller closed-loop control shall maintain coolant temperature to ±0.5°C of set-point. — Verification method: Test.

CF-006 Sample cooling shall be monitored with temperature feedback; an alarm shall activate if workpiece support temperature exceeds the defined threshold (TBD). — Verification method: Demonstration.

3. System Top-Level Flow

3.1 Main Material Flow

The main material flow defines the sequence of operations for each plate from raw input to finished cut parts. The following table specifies all steps, responsible modules, outputs, and branching conditions.

Step	Action	Actor / Module	Outputs / Conditions	Next Step
1	Operator loads plate batch onto plate rack (up to 25 plates, max height 495 mm).	Operator	Plates staged; height sensor confirms batch present.	Step 2
2	System performs startup self-check: laser power, focus cal., axis homing, gas pressures, sensor functionality, all safety interlocks.	Computing & Calculations	Self-check PASS → production mode enabled. FAIL → HMI alert + fault log.	Step 3 if PASS
3	Auto plate loader picks top plate from rack and transfers to cutting table.	Plate Loading Mechanics	Plate positioned on slat table; vacuum / clamp engaged.	Step 4
4	Coaxial vision system performs plate identification and edge-finding; aligns coordinate frame to plate.	Control & Feedback + Coaxial Camera	Plate origin & orientation confirmed; nesting offset applied to NC program.	Step 5
5	CNC executes nested cut program: BPP mode auto-selected per feature geometry; adaptive control loop active.	CNC / Beckhoff TwinCAT	Parts cut; OCT monitors kerf depth; photodiode monitors plasma; pyrometer monitors temperature.	Step 6
6	Completed cut parts and skeleton frame remain on table; Z-axis retracts; assist gas off.	Sample Mechanics	Laser off; table ready for unloading.	Step 7
7	Cut parts transferred to output staging / unloading platform. Skeleton / scrap directed to debris bin.	Plate Loading Mechanics + Debris Removal	Parts delivered to output; scrap in bin.	Step 8
8	Slag / dross collected in	Operator (periodic)	Cutting zone clear.	Step 9

	drawer below slat table; operator empties at defined intervals.			
9	System checks: plates remaining in batch? If yes → Step 3. If no → batch complete, HMI alert to operator.	Computing & Calculations	Batch counter decremented. Idle / ready for next batch.	Step 3 or END

Note: the above flow assumes nominal operation. Fault branches during Steps 2–8 invoke Section 3.3 Error Handling procedures.

3.2 Calibration Process Flow

The calibration flow defines the automated calibration sequences for laser power verification (prefix P), motion axes (prefix M), and BPP beam characterisation (prefix B). All sequences shall be executable without disassembly of the machine.

Step	Action	Trigger / Frequency	Pass Criterion	Fail Action
P1	Beam splitter measurement: split-off power meter reads actual beam power at 5 operating levels.	Every power-on + periodic (configurable interval, default every 4 hrs)	Measured power within ±0.5% of commanded set-point at each level.	Flag fault; block production; alert operator.
P2	Compare split-off reading against Ophir Optronics reference (traceable calibration).	At scheduled maintenance or on P1 drift detection	Offset within ±0.5%; correction applied to power table.	Recalibrate power table; if still out, service laser.
M1	All axes execute homing sequence; absolute encoder reference positions verified.	Every power-on	All axis home positions within ±5 µm of stored reference.	Flag homing fault; inhibit motion; alert operator.
M2	X and Y axis straightness and bidirectional repeatability verified using coaxial vision + calibration artifact.	Weekly or after any mechanical intervention	Positioning accuracy ±10 µm, repeatability ±5 µm over full travel.	Recalibrate servo loop gain; update compensation map; escalate if unresolved.
M3	Z-axis focus reference calibrated: capacitive sensor zeroed to known standoff on calibration target.	Every power-on	Focus standoff within ±5 µm of nominal.	Flag focus fault; alert operator.
B1	BPP mode transition verified: beam profiler (or burn pattern on anodized Al) confirms spot diameter in fine and power modes.	After laser source change or head service; monthly	Fine mode spot ≤35 µm; power mode spot 200–300 µm.	Adjust zoom collimator; re-qualify with vendor if unresolved.

3.2.1 Power Auto-Calibration

CAL-001 The laser power shall auto-calibrate periodically (default every 4 hours and at every power-on) using the split-off power meter to verify set-point accuracy against the reference standard. — Verification method: Demonstration.

3.2.2 Motors Auto-Calibration

CAL-002 All motion axes shall execute an automated calibration and homing procedure at every power-on and periodically (weekly). The sequence shall verify absolute encoder reference, axis straightness, Z-focus reference, and bidirectional repeatability. — Verification method: Demonstration.

3.2.3 BPP Mode Calibration

CAL-003 The BPP fine and power modes shall be verified monthly and after any laser source or head service, using a coaxial burn-pattern method on anodized aluminum or an integrated beam profiler. Results shall be logged with timestamp. [Demonstration]

3.3 Error Handling

The error handling framework classifies all faults into four severity levels: CRITICAL, HIGH, MEDIUM, and LOW. The table below defines the expected system response and operator recovery procedure for each category.

Fault Category	Example Triggers	Immediate System Response	Recovery Procedure
CRITICAL — Laser Safety	Door interlock open during operation; safety PLC fault; laser enable chain broken	Laser shutdown within 10 ms; all axes decelerate to stop; laser shutter closes; red warning light on.	Operator clears fault; safety PLC reset by authorised personnel; system self-check before resume.
CRITICAL — E-Stop	Any E-stop button pressed	All motion and laser off within 500 ms; controlled deceleration; system latched in safe state.	Manual reset by authorised operator after inspection.
CRITICAL — Fire / Fume	Smoke/thermal sensor alarm inside enclosure	Immediate laser shutdown; fume extractor at maximum; enclosure alarm; operator alert (HMI + SMS).	Do not re-enter until safe; identify fire source; service before restarting.
HIGH — Gas Fault	N_2 pressure out of range; O_2 leak detected; proportional valve fault	Laser and cutting halted; gas shutoff valve closes; HMI error code and guidance text logged.	Operator inspects gas supply; replace faulty valve/regulator; re-pressurise and verify.
HIGH — Process Deviation	OCT kerf depth out of bounds; plasma backscatter high; cut quality classification FAIL	Adaptive control attempts correction (power / speed / gas adjustment). If not resolved in 3 cycles: pause cut, log event.	Operator inspects nozzle / lens / material; adjust process recipe; re-run test cut.
MEDIUM — Axis Fault	Servo drive following error; encoder reference lost; limit switch triggered	Motion inhibited on affected axis; laser off; HMI alert with axis ID and error code.	Re-home affected axis; check mechanical clearances; replace encoder if reference lost.
MEDIUM — Thermal	Chiller temperature out of range; laser head temperature high; gantry temperature drift alarm	Power-de-rate laser; log thermal event; alert operator.	Inspect chiller; check coolant flow; adjust chiller set-point.
LOW — Consumable / Maintenance	Nozzle wear (based on usage counter); lens degradation (scattered light >5%); fume filter pressure drop	Predictive maintenance alert on HMI (amber indicator); no production inhibit unless threshold exceeded.	Scheduled replacement at next shift change; confirm via HMI.

ERR-001 All fault conditions shall generate a descriptive error code and operator guidance message on the HMI. — Verification method: Demonstration.

ERR-002 All error events shall be logged with timestamp, error code, machine state, and operator-acknowledged recovery action, retained for ≥ 1 year. — Verification method: Demonstration, Test.

ERR-003 Critical faults (laser interlock, E-stop, gas over-pressure, fire detection) shall immediately transition the machine to a safe state and latch until cleared by an authorised operator. — Verification method: Demonstration, Test.

4. External Interfaces

4.1 Communication Interfaces

IF-001 [Optional] Facility WiFi connectivity: the system may support connection to the facility WiFi network for remote monitoring. — Verification method: Demonstration.

IF-002 [Optional] Internet connectivity: the system may support secured internet connectivity for remote support and auto-updates. — Verification method: Demonstration.

IF-003 OPC UA server: the system shall expose an OPC UA server interface for integration with facility MES / ERP systems. — Verification method: Demonstration, Test.

4.2 Mechanical Interfaces

IF-004 Plate input interface: the system shall accept plates from a facility loading platform or pallet rack with height range per PL-001. Interface dimensions TBD. — Verification method: Inspection.

IF-005 Plate output interface: the system shall transfer cut parts and skeleton/scrap to a facility unloading platform. Interface TBD. — Verification method: Inspection.

4.3 Electrical Interfaces

IF-006 Main power inlet: 480 VAC 3-phase high-power inlet; rated current TBD based on final BOM. — Verification method: Inspection.

4.4 Coolant Interface

IF-007 Coolant inlet: 3-inch hose connection supplying clean water at room temperature, 15 L/min. [Inspection]

IF-008 Coolant outlet: 3-inch hose connection returning water at up to 74°C, 15 L/min. [Inspection]

4.5 Gas Interfaces

IF-009 Nitrogen assist gas: facility supply of N_2 at ≥ 25 bar; peak flow rate TBD. — Verification method: Inspection.

IF-010 Oxygen assist gas [optional]: facility supply of O_2 at ≥ 6 bar for reactive cutting. — Verification method: Inspection.

4.6 GUI Interface

IF-011 Operator HMI: job setup, part program loading, real-time display of position / laser parameters / sensor feedback / gas pressures / status / alarms, nesting preview, manual jog, calibration initiation. — Verification method: Demonstration.

IF-012 A remote read-only monitoring interface shall be accessible via secure VPN / web dashboard with KPI display and alarm notifications. — Verification method: Demonstration.

5. Internal Interfaces

5.1 Interlocks

INT-001 Laser safety interlocks: covers protecting the laser/optics service area and the internal target service area shall each have independent interlocks commanding laser shutdown within 10 ms of cover opening. — Verification method: Test.

INT-002 Key override: a physical administrator key shall enable service-mode access with covers open; the machine shall be classified Laser Class 4 and appropriate visual warnings shall be active. — Verification method: Demonstration.

INT-003 Gas delivery interlocks: the gas delivery system shall include leak detection sensors, automatic pressure-relief devices, and automatic shutoff on any detected fault.

INT-004 Fire detection: a smoke/thermal sensor inside the enclosure shall trigger automatic laser shutdown and operator alert. — Verification method: Demonstration, Test.

6. Software Features

6.1 Software Alerts

SW-001 The software shall generate automated operator alerts (on-screen HMI + optional email/SMS) for: all fault conditions, consumable wear, axis overload, door/interlock events, gas pressure out of range, and temperature anomalies. — Verification method: Demonstration.

SW-002 Predictive maintenance alerts shall be generated based on laser operating hours, optics degradation trends, motion system wear indicators, and consumable usage tracking. — Verification method: Demonstration.

6.2 Part Program and CAM

SW-003 The system shall accept standard industrial geometry file formats: DXF, DWG, STEP, IGES. — Verification method: Demonstration.

SW-004 The CAM/nesting module shall automatically generate optimised nesting layouts achieving ≥ 85% material utilisation for typical mixed-part jobs. Manual nesting override shall also be supported. — Verification method: Demonstration.

SW-005 The cutting path planner shall implement ≥ 200-segment look-ahead for smooth velocity profiling at corners and curves. — Verification method: Test.

SW-006 The software shall implement automatic BPP mode selection based on part geometry analysis (feature size threshold, configurable). — Verification method: Demonstration.

SW-007 A process parameter database shall store, version-control, and associate parameter sets (laser power, BPP mode, speed, gas type, gas pressure, focus position, nozzle standoff) with material type, thickness, and quality level. — Verification method: Demonstration.

6.3 Data Logging and Traceability

SW-008 All process parameters and sensor data shall be logged at ≥ 1 kHz with timestamped storage, retained for ≥ 1 year. [Test]

SW-009 All parameter changes shall be logged with operator ID, timestamp, and previous/new values.

6.4 System Software

SW-010 Boot time from power-on to operational readiness shall not exceed 120 seconds. — Verification method: Test.

SW-011 The software shall implement automatic nozzle centering calibration using the coaxial vision system. — Verification method: Demonstration.

SW-012 Remote software updates shall be supported via secured network; updates shall not overwrite calibration data or process parameters without explicit operator confirmation. — Verification method: Demonstration.

7. Safety Requirements

SA-001 The system shall comply with CE Marking directives: Machinery Directive 2006/42/EC, EMC Directive 2014/30/EU, and Low Voltage Directive 2014/35/EU.

SA-002 Laser safety classification per IEC 60825-1: Class 1 with all enclosure panels closed; Class 4 with laser/optics service covers open (key override required). — Verification method: Test.

SA-003 Safety system integrity: the laser shutdown safety function shall achieve SIL-2 per EN 62061 / ISO 13849-1 Category 3 PL d minimum. — Verification method: Test, Analysis.

SA-004 E-stop: emergency stop buttons shall be accessible from all operator positions and shall bring the machine to a safe state within 500 ms. — Verification method: Test.

SA-005 Enclosure attenuation: the enclosure shall attenuate 1070–1080 nm radiation to below MPE at all external surfaces (OD ≥ 7). — Verification method: Test.

SA-006 Fume extraction: the system shall maintain all metal particulate levels below occupational exposure limits per EN 689 at all operator positions. Minimum airflow: ≥ 3000 m^3/hr with HEPA (99.97% at 0.3 μm) and activated carbon filtration. — Verification method: Test.

SA-007 Noise: machine noise emission shall not exceed 80 dB(A) at 1 m from the enclosure during cutting. — Verification method: Test.

SA-008 A documented safety validation plan shall be executed before first operation and at defined service intervals. — Verification method: Analysis, Demonstration.

SA-009 Visual warning: red/green laser-status indicator lights shall be visible from all operator positions. — Verification method: Inspection.

SA-010 Electrical safety: main disconnect accessible; protective earth ≤ 0.1 Ω; RCD ≤ 30 mA. — Verification method: Test.

8. Process and Environmental Requirements

PR-001 Nitrogen assist gas: supply at up to 25 bar with electronically-controlled proportional valves, pressure accuracy ±0.2 bar. [Test]

PR-002 Oxygen assist gas [optional]: supply at up to 6 bar for reactive cutting. — Verification method: Test.

PR-003 Gas pressure closed-loop control: gas pressure shall be adjustable and maintained in closed-loop with proportional valves. — Verification method: Test.

PR-004 Optics purge: compressed-air-driven air knife or lens purge to protect lower optics. Compressed air quality: ISO 8573-1 Class 1.4.1. — Verification method: Inspection.

PR-005 Chiller stability: process chiller shall maintain laser coolant at 20 ± 0.5°C with capacity ≥ 15 kW. — Verification method: Test.

PR-006 Slag/dross collection shall be accessible without entering the cutting zone. — Verification method: Inspection.

PR-007 Factory environment assumption: 18–28°C, < 80% RH non-condensing, clean dry compressed air, adequate 3-phase electrical supply. Climate control is the facility's responsibility. — Verification method: Analysis.

9. Quality Assurance Requirements

QA-001 Automated calibration: the system shall include a routine verifying positioning accuracy across the full work area using the coaxial vision system and reference artifacts. — Verification method: Demonstration.

QA-002 Edge quality: Ra ≤ 3.2 μm for Stainless-steel at thickness ≤ 6 mm; Ra ≤ 6.3 μm for 6–15 mm. — Verification method: Test.

QA-003 In-process kerf measurement: the OCT system shall measure kerf width and depth to verify minimum feature compliance. — Verification method: Test.

QA-004 A standardised test part (defined geometry) shall be cut and measured externally to verify all cutting specifications at acceptance and at defined intervals. — Verification method: Demonstration.

QA-005 Startup self-check: at every power-on the system shall verify laser output power, focus calibration, axis homing, sensor functionality, gas pressures, and all safety interlocks before enabling production mode. — Verification method: Demonstration.

QA-006 Beam quality (M^2 or BPP) shall be measurable at defined maintenance intervals using an integrated or attachable beam diagnostic. — Verification method: Demonstration.

QA-007 The process parameter database shall include acceptance criteria (pass/fail bounds) for each monitored sensor, enabling automatic quality classification of each cut. [Demonstration]

Preliminary BOM Cost Estimate

Table B.1 — Top-level BOM estimate for Architecture C at initial production volumes (10–20 units/year). Prices reflect expected negotiated pricing from primary vendors.

Subsystem / Component	Low Est.	High Est.	Notes
Laser source (variable-BPP, 6–8 kW)	$35 K	$60 K	IPG AMB / Coherent ARM / Raycus ABP range
Cutting head & optics (zoom head, protective optics, nozzles)	$10 K	$20 K	Precitec ProCutter 2.0 prototype; Raytools for production
Process sensors (OCT, photodiodes, pyrometer, camera, AE)	$18 K	$30 K	OCT is major cost item; optional in base config
Motion system (linear motors, encoders, guides, Z-axis)	$15 K	$28 K	Etel / Beckhoff / Heidenhain
CNC & servo drives (controller, drives, I/O modules)	$8 K	$15 K	Beckhoff CX + AX5000 EtherCAT
Safety system (safety PLC, interlocks, light curtains, enclosure panels)	$3 K	$6 K	Pilz / Sick; OD≥7 panels
Enclosure & frame (laser-safe	$15 K	$25 K	Custom cast base; enclosure outsourced

enclosure + polymer concrete base + gantry)			
Work table (shuttle table, slats, drives)	$5 K	$10 K	Semi-custom
Gas delivery (regulators, proportional valves, manifold, piping, nozzle set)	$3 K	$6 K	Festo / SMC proportional valves
Process chiller (15–20 kW)	$3 K	$6 K	SMC HRS / S&A CW-6000
Fume extraction (HEPA + carbon, ducting, segmented plenum)	$8 K	$15 K	Kemper / Plymovent
Electrical cabinet (wiring, connectors, PDU, UPS)	$5 K	$8 K	Standard
Software & licences (CNC, HMI, CAM integration, custom SW)	$3 K	$8 K	Beckhoff + custom development
Assembly, test materials, cables, fasteners, consumables	$3 K	$5 K	Estimate
TOTAL ESTIMATED BOM	**$134 K**	**$242 K**	Target $150–165 K achievable by selecting mid-range laser + Raytools head for production units.

NOTE: Cost optimisation strategy: define a base configuration at $150 K BOM (without OCT) and offer the advanced sensor suite (OCT + coaxial camera) as a premium $20–30 K option. This allows the product to meet the price target while offering a differentiated premium version.

Design Guidelines

The following guidelines apply to subsystem design. They are engineering best-practice constraints, not verifiable requirements.

- Gantry base material: polymer concrete or mineral cast preferred over welded steel for superior thermal inertia and vibration damping. CTE target ≤ 10 ppm/K.
- Linear motors: ironless linear motors (zero cogging) on X and Y axes to eliminate velocity ripple at slow cutting speeds.
- Moving mass budget: design all head carriages to the ≤ 25 kg moving mass limit from the outset; this constrains cable management, gas connections, and sensor mounting.
- BPP mode-switching: validate laser-to-head beam delivery across the full BPP range before committing to a cutting head vendor. Allocate 4–6 weeks for this qualification programme.
- EMC zoning: physically separate power electronics (laser PSU, servo drives) from signal electronics (sensor interfaces, CNC) with shielded partitions and dedicated clean earth for signal electronics.
- Process parameter development: allocate 3–6 months dedicated process development time and $20–30 K test-material budget after mechanical/electrical integration. Target ≈ 200–300 parameter sets (2 materials × 10–15 thicknesses × quality levels).
- Software architecture: implement adaptive control on a real-time platform (Beckhoff TwinCAT 3 with XFC modules). Begin with open-loop parameter tables and progressively close loops during commissioning.
- Vendor engagement: engage the selected laser source vendor (IPG or Coherent) early for beam delivery qualification support — this is on the critical development path.

Future Features

The following are planned for future product generations and shall be considered in platform architecture decisions.

- N+1 generation: support metal plate thickness up to 25 mm.
- N+2 roadmap: support cutting Titanium alloys.
- Optional premium configuration: full coaxial OCT + advanced sensor suite as a $20–30 K upgrade package over the base configuration.
- Robotic material handling: full robotic loading and unloading platform (not in V1 scope).
- Additional regional certifications: UL / cUL for North American market (not in V1 scope).

Open Items

The following items require resolution before Preliminary Design Review (PDR).

7. CRITICAL: Product management shall formally accept or revise the 35 µm minimum feature requirement against the thickness-dependent specification in Table 1.1. If 35 µm at 15 mm is truly non-negotiable, the project must be re-scoped as a research programme with significantly increased budget and timeline.
8. Laser source selection: beam delivery qualification required with selected cutting head (4–6 week evaluation campaign).
9. Gantry FEA: detailed structural analysis needed to finalise polymer concrete base, cross-beam material, and thermal compensation sensor layout.
10. OCT integration: confirm spectral compatibility between laser wavelength, protective window, and OCT path (e.g. Precitec IDM validation).
11. Machine length (ARCH-002): finalise total machine length once mechanical layout is complete.
12. Plate geometry: confirm exact dimensions and alloy grades of all 25 plates per batch to finalise nesting strategy and gantry stroke.
13. N_2 gas peak flow rate: determine at full cutting power to size the facility supply connection (IF-009).
14. Sample cooling temperature threshold (CF-006): define workpiece support maximum temperature limit.

Requirement Tracking Table

All requirements in this document are traced below. Priority order: (1) sysreq_example Ver 1.1, (2) Claude-SRD Rev A, (3) supplementary analysis.

Req ID	Requirement Title	Source	Comments
PERF-001	Metal type – Aluminum	Prod 000-000 #1	
PERF-002	Metal type – Stainless-steel	Prod 000-000 #1	
PERF-003	Plate dimensions max	Prod 000-000 #2	
PERF-004	Cutting speed – line speed	Prod 000-000 #12	125 m cuts/hr minimum
PERF-005	Throughput – parts/hr	Claude-SRD SYS-004	25–50 parts/hr; complements PERF-004
PERF-006	Machine up-time	Prod 000-000 #14	sysreq >99.5% overrides Claude-SRD 97%
ARCH-001	Max BOM cost	Prod 000-000 #4	$150 K target; $165 K hard ceiling per Claude-SRD
ARCH-002	Machine dimensions	Prod 000-000 #15	Width/height from sysreq; total footprint from Claude-SRD
ARCH-003	Plate batch size	Prod 000-000 #13	25 plates
ARCH-004	System architecture	Claude-SRD Arch C	Variable-BPP over ChatGPT Arch A (conventional CW)
ARCH-005	Serial production intent	Claude-SRD SYS-011	≥10 units/yr
ARCH-006	MTBF	Claude-SRD SYS-007	>2000 hrs
ARCH-007	Cold-start readiness	Claude-SRD SYS-014	15 min from power-on
ARCH-008	Total power consumption	Claude-SRD SYS-010	≤30 kW sustained
LO-001	Cut line resolution	Prod 000-000 #3	<17.5 µm for 35 µm feature per sysreq_example
LO-002	Feature size – thickness dep.	Claude-SRD Table 1.1	Physics feasibility; open item flagged
LO-003	Laser wavelength	Prod 000-000 #1	1070–1080 nm from sysreq_example
LO-004	Laser source power	Prod 000-000 #2	Up to 12 kW per sysreq_example
LO-005	Power increments	Prod 000-000 #2	2.5%±0.1% from sysreq_example POC
LO-006	Beam focus focal length	Sysreq 2.2.5	75 mm
LO-007	Beam DOF	Sysreq 2.2.5	15 mm at 30 lp/mm MTF>60%
LO-008	BPP range & switching	Claude-SRD OP-001,004	0.8–8 mm·mrad; ≤50 ms switch

LO-009	Spot diameter range	Claude-SRD OP-006	30–300 µm
LO-010	Focus adjustment range	Claude-SRD OP-005	±15 mm, ±5 µm accuracy
LO-011	Coaxial vision resolution	Claude-SRD OP-007	≥5 µm/pixel
LO-012	Nozzle standoff	Claude-SRD OP-012	0.3–3.0 mm, ±0.05 mm
LO-013	Window monitoring	Claude-SRD OP-010	Alert before >5% BQ degradation
LO-014	Laser safety – closed	Sysreq 2.2.8	Class 1
LO-015	Laser safety – service open	Sysreq 2.2.9/2.2.10	Class 4 + key; sysreq overrides Claude-SRD always-Class-1
LO-016	Laser cooling	Sysreq 2.2.11.1	20±0.5°C, ≥15 kW chiller
LO-017	Laser coolant type	Sysreq 2.2.11.2	Room-temp water
LO-018	Optics lifetime	Claude-SRD OP-009	<1% degradation per 1000 hrs
ME-001	Gantry positioning accuracy	Claude-SRD ME-001	±10 µm; ChatGPT 1 µm rejected as infeasible
ME-002	Gantry repeatability	Claude-SRD ME-002	±5 µm
ME-003	Max traverse speed	Claude-SRD ME-003	≥100 m/min
ME-004	Gantry acceleration	Claude-SRD ME-004	≥1.0 G
ME-005	Gantry thermal drift	Claude-SRD ME-006	≤5 µm/°C
ME-006	Base material resonance	Claude-SRD ME-005	≥80 Hz, polymer concrete
ME-007	Z-axis specification	Claude-SRD ME-008	±5 mm, 1 µm res., ≥100 Hz BW
ME-008	Moving mass budget	Claude-SRD ME-010	≤25 kg
ME-009	Nozzle vibration	Claude-SRD ME-011	≤2 µm RMS at 10 m/min
ME-010	Sample active cooling	Sysreq 2.3.2.1	
PL-001	Batch height	Prod 000-000 #13	Max 495 mm; min 0.5 mm
PL-002	Auto plate loading	Prod 000-000 #13	One-by-one
PL-003	Table exchange time	Claude-SRD ME-012	≤60 s
EL-001	Laser source power supply	Sysreq 2.5.1	480 VAC; sysreq overrides Claude-SRD 380–480 V
EL-002	Optics focus motor supply	Sysreq 2.5.2	12 VDC 0.5 A
EL-003	Servo update rate	Claude-SRD EL-001	≥4 kHz
EL-004	Encoder resolution	Claude-SRD EL-002	≤0.1 µm
EL-005	Safety PLC SIL	Claude-SRD EL-010	SIL-2, DC≥99%
EL-006	Sensor sampling	Claude-SRD EL-005	≥100 kHz, ≥16 bit
EL-007	UPS / controlled shutdown	Claude-SRD EL-007	On power loss
EL-008	EMC emissions	Claude-SRD EL-008	EN 55011 Grp 2 Class A
EL-009	EMC immunity	Claude-SRD EL-009	EN 61000-6-2
CF-001	Power measurement method	Sysreq 2.6.1.1	Split-off from main beam
CF-002	Power measurement accuracy	Sysreq 2.6.1.2	±0.5%; stricter than Claude-SRD ±1%
CF-003	Power control increments	Sysreq 2.6.1.3	2.5%±0.1%
CF-004	Real-time adaptive control	Claude-SRD 3.3.1	≥4 kHz; multi-sensor fusion
CF-005	Chiller control	Claude-SRD PR-005	20±0.5°C
SA-001	CE compliance	Claude-SRD SYS-009	MD, EMC, LVD directives
SA-002	Interlock response	Claude-SRD SA-002	≤10 ms laser disable
SA-003	E-stop response	Claude-SRD SA-004	≤500 ms to safe state
SA-004	Safety system SIL	Claude-SRD SA-003	SIL-2 EN 62061
SA-005	Enclosure OD	Claude-SRD SA-005	OD≥7 at 1 µm
SA-006	Fume extraction	Claude-SRD PR-007	≥3000 m³/hr; overrides ChatGPT 1500 m³/hr

SA-007	Noise	Claude-SRD SA-009	≤80 dB(A) at 1 m
SA-008	Safety validation plan	Claude-SRD SA-010	Before first op + intervals
SW-001	SW alerts	Sysreq 6.1	Fault, wear, overload, gas, temp
SW-002	File formats	Claude-SRD SW-002	DXF, DWG, STEP, IGES
SW-003	Nesting utilisation	Claude-SRD SW-003	≥85%
SW-004	Look-ahead	Claude-SRD SW-014	≥200 segments
SW-005	BPP auto mode	Claude-SRD SW-006	Geometry-based
SW-006	Process recipe DB	Claude-SRD SW-007	CRUD, version control
SW-007	Data logging rate	Claude-SRD SW-005	≥1 kHz, ≥1 yr retention
SW-008	Boot time	Claude-SRD SW-010	≤120 s
SW-009	Nozzle centering	Claude-SRD SW-011	Auto via coaxial vision
CAL-001	Power auto-calibration	Prod 000-000 #11	Periodic
CAL-002	Motors auto-calibration	Prod 000-000 #11	Homing + straightness
CAL-003	Startup self-check	Claude-SRD QA-006	All subsystems
IF-001	Facility WiFi	Prod 000-000 #23	Optional
IF-002	Internet connectivity	Prod 000-000 #23	Optional
IF-003	OPC UA	Claude-SRD SW-013	MES/ERP integration
IF-004	Power inlet	Sysreq 4.3.1	480 VAC 3-phase
IF-005	Coolant inlet	Sysreq 4.4.1	3" hose, 15 L/min
IF-006	Coolant outlet	Sysreq 4.4.2	3" hose, ≤74°C, 15 L/min
QA-001	Auto calibration routine	Claude-SRD QA-001	Coaxial vision + artifacts
QA-002	Edge quality Ra	Claude-SRD QA-002	Ra≤3.2 μm (SS ≤6 mm)
QA-003	In-process kerf meas.	Claude-SRD QA-003	OCT
QA-004	Test part protocol	Claude-SRD QA-004	Standard geometry
QA-005	Audit trail	Claude-SRD QA-005	Operator ID + timestamp
QA-006	Beam quality meas.	Claude-SRD QA-007	M^2 or BPP at maintenance intervals
QA-007	Auto quality classification	Claude-SRD QA-008	Pass/fail per sensor bounds