Pico-Scale Welding

Nanoscale Material Joining: Feasibility Analysis and Architecture Down-Selection

Technical Specification

Document Reference: AG-2025-0104-5562

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1. Overview

This document presents a feasibility analysis for pico-scale welding technology targeting precision material joining at the nanoscale. Following comprehensive technical review and stakeholder assessment, the Electrospray Nanowelding architecture has been approved for Phase 1 development, with alternative architectures (Atomic Fountain Deposition and Plasma Bridge Welding) terminated based on fundamental physics constraints.

The programme operates within a €670,000 envelope over 20 months, targeting Fan-Out Wafer-Level Packaging (FOWLP) redistribution layer (RDL) repair at line/space geometries of 2 μm and above. The assessed fragility of 78% (22% success probability) is consistent with exploratory R&D at this budget scale, with risk characterised, bounded, and mitigated through defined fallback strategies.

2. Operational Definitions

2.1 Nanoscale Thermal Regime

The nanoscale thermal regime describes the length scale (1-100 nm) where classical heat conduction models break down. At these dimensions, ballistic phonon transport dominates, requiring the Two-Temperature Model (TTM) to describe electron-lattice energy exchange under ultrafast heating. Surface energy begins to dominate volume energy in material behaviour. This regime is operationally defined by the condition where the characteristic dimension is less than the electron or phonon mean free path (typically 10-50 nm for metals at room temperature).

2.2 Precision Material Joining

Precision is defined relative to quantified baselines: achieving positional accuracy of ±50 nm (1σ) and volumetric control within ±20% of target. This compares to Focused Ion Beam Induced Deposition (FIBID) benchmarks of ±10 nm positional accuracy and ±10% volumetric control.

2.3 Heat-Affected Zone Target Derivation

The 500 nm Heat-Affected Zone (HAZ) target derives from three independent constraints. First, TTM electron diffusion length: under femtosecond laser heating, hot electrons diffuse at near-Fermi velocity for approximately 50 ps before equilibrating with the lattice, yielding a diffusion length of approximately 70 nm with a 2× safety factor providing a conservative bound of 140 nm. Second, superconducting coherence length: for Al-based Josephson junctions, the coherence length in the dirty limit is 300-400 nm, requiring HAZ to exceed this value. Third, competitive parity: LoTIS-FIBID achieves HAZ of 200-500 nm. The 500 nm target represents the intersection of physical limits, application requirements, and competitive positioning.

2.4 Production Density

Production density means electrical resistivity within 3× of bulk material value, measured via 4-point probe:

Material	Bulk Resistivity	Target (≤3×)
Au	2.2 μΩ·cm	≤6.6 μΩ·cm
Cu	1.7 μΩ·cm	≤5.1 μΩ·cm
Ag	1.6 μΩ·cm	≤4.8 μΩ·cm

2.5 Material-Specific Performance Expectations

Positioning performance varies by material due to oxidation and sintering characteristics:

Material	Expected Positioning	Application Viability	Notes
Au	500 nm - 2 μm	**PRIMARY TARGET**	Best-characterised; lowest oxidation
Ag	1 - 3 μm	**PRIMARY TARGET**	Slightly higher variability
Cu	2 - 5 μm	FALLBACK	Oxidation increases spread
SnAgCu solder	3 - 8 μm	MARGINAL	Multi-phase sintering challenges

Programme viability requires Au positioning below 5 μm. Catastrophic threshold is defined as Au positioning exceeding 20 μm, indicating fundamental process failure.

3. Architecture Status

Three candidate architectures were evaluated. Final status:

Architecture	Status	Rationale
Atomic Fountain Deposition	**TERMINATED**	No closed cycling transitions for Au/Cu/Al
Plasma Bridge Welding	**TERMINATED**	Stochastic tunnelling; substrate damage
Electrospray Nanowelding	**APPROVED**	Physics valid; niche applications viable

4. Technical Requirements

4.1 Sintering Parameters

Target sintering times are based on published experimental data:

Source	Material	Size	Time	Resistivity
Ko et al. 2007	Au	5 nm	60 s	4.8× bulk
Perelaer et al. 2012	Ag	40 nm	120 s	2.5× bulk
Kang et al. 2018	Cu	20 nm	180 s	3.2× bulk
This programme (target)	Au	30 nm	90 s	≤3× bulk

Note: FOWLP RDL repair occurs on heterogeneous surfaces versus controlled substrates in published literature. Phase 1 will characterise actual sintering on FOWLP test structures; if sintering times exceed 180 seconds, cycle time targets are invalidated.

4.2 Tail Latency Budget

Cycle time variance distribution for production planning:

Percentile	Sintering Time	Total Cycle	Impact
P50 (median)	90 s	3.5 min	Normal operation
P90	150 s	5.5 min	Schedule buffer required
P99	240 s	8.5 min	Alarm; investigate root cause
P99.9	>300 s	>10 min	Abort joint; flag for review

P99 events are expected approximately 1 in 100 joints. At 60 joints per day, this means approximately 1 P99 event every 2 days. Systems must accommodate without operator intervention. Schedule planning assumes 10% buffer for tail latency, yielding effective throughput of 54 joints per day.

5. Implementation Approach

5.1 Phase 1 Budget (€670,000 Envelope)

Line Item	Base	Contingency	Envelope
Personnel (2 FTE × 20 mo)	€300,000	€30,000	€330,000
Electrospray source	€80,000	€10,000	€90,000
Femtosecond laser	€60,000	€50,000	€110,000
Positioning stage	€35,000	€5,000	€40,000
Metrology	€25,000	€5,000	€30,000
Consumables	€20,000	€5,000	€25,000
Shadow hire (0.5 FTE × 20 mo)	€50,000	€5,000	€55,000
LoTIS deposit	€50,000	€0	€50,000
zeroK price reserve	€0	€10,000	€10,000
COMMITMENT AUTHORITY	**€550,000**	—	—
CONTINGENCY (ring-fenced)	—	**€120,000**	—
TOTAL ENVELOPE	—	—	**€670,000**

5.2 J-Curve Cost Model

Cost per joint follows a worse-before-better trajectory:

Phase	Period	Cost/Joint	Explanation
Integration friction	M1-6	∞ (no joints)	System assembly; no production
Early prototype	M7-12	€500-1000	Low yield; high rework; learning curve
Late prototype	M13-18	€100-200	Process stabilisation; improving yield
Phase 1 exit	M19-20	€50-80	Demonstration-grade; not production
Phase 2 target	M24-36	€20-35	Production-grade with optimisation
Mature system	Year 3+	€10-20	Requires Phase 2 investment

5.3 Utilisation Factor Analysis

Unit economics sensitivity to equipment utilisation:

Scenario	Utilisation	Effective Hours	Joints/Day	Cost/Joint
Ideal (100%)	100%	8.0 hr	60	€33
High utilisation	80%	6.4 hr	48	€42
Typical fab	**65%**	**5.2 hr**	**39**	**€51**
Low utilisation	50%	4.0 hr	30	€67

Planning assumption: 65% utilisation (typical fab environment with changeovers, maintenance, calibration). Effective cost €51/joint in Phase 2 mature state. Business case requires packages with scrap value exceeding €150.

5.4 Five-Year Lifecycle Cost Model

Cost Category	Year 1	Year 2	Year 3	Year 4	Year 5	5-Year
Phase 1 (this proposal)	€550k	€120k*	—	—	—	€670k
Phase 2 development	—	€400k	€300k	—	—	€700k
Equipment (production unit)	—	—	€800k	—	—	€800k
Personnel (1.5 FTE ops)	—	—	€75k	€115k	€115k	€305k
Consumables	—	—	€30k	€50k	€50k	€130k
Maintenance	—	—	€40k	€80k	€80k	€200k

Facility (cleanroom allocation)	—	—	€25k	€25k	€25k	€75k
CUMULATIVE	**€550k**	**€1,070k**	**€2,340k**	**€2,610k**	**€2,880k**	**€2,880k**

**Year 2 includes Phase 1 contingency draw if required. Breakeven at €51/joint requires approximately 56,000 joints over 5 years (approximately 15,000 joints/year in Years 3-5).*

6. Market Validation

6.1 Primary Market: FOWLP RDL Repair

Market parameters derived from primary sources:

Parameter	Value	Source (Primary)
Global FOWLP market	$4.2B (2024)	Yole Advanced Packaging 2023
RDL defect rate	2-5%	TSMC 2023 ESG Report
Repairable fraction	25-40%	ASE 2022, Amkor Q3 2023, Yole 2023
SAM at €51/joint	~$4-6M/yr	Packages with scrap >$150

6.2 Market Positioning

Electrospray targets sub-5 μm repair where traditional wire bonding (applicable at >10 μm scale) is not feasible. This represents market expansion into currently unserved segments, not displacement of existing solutions. If Electrospray achieves only >10 μm positioning, it offers no value over existing wire bonding and the programme should terminate.

6.3 Atmospheric Operation Trade-offs

Factor	UHV (FIBID)	Ambient (Electrospray)	Assessment
Particulate	None	ISO Class 5 glovebox	Disadvantage
Oxide formation	Minimal	N_2 purge required	Disadvantage
Facility cost	€185-280k	€55-105k	€100-175k advantage

7. Regulatory and Liability Framework

7.1 Liability Assignment

Failure Mode	Primary Liable Party	Secondary	Contractual Mechanism
Equipment malfunction	Equipment Vendor	—	Standard product warranty
Operator error	Repair Operator	—	PI insurance required
Recipe defect (vendor)	Equipment Vendor	—	Recipe warranty clause
Recipe defect (modified)	Repair Operator	—	Modification log + waiver
Repaired device field failure	Repair Operator	OEM (spec)	Indemnification clause

7.2 Professional Indemnity Requirements

- Equipment purchaser: €5M PI coverage required before equipment shipment
- Service provider: €10M PI coverage; annual certificate to customers

8. Organisational and Staffing Plan

8.1 Shadow Hire Execution

Shadow hire is identified as a key risk factor with less than 40% probability of M3 fill:

Timeline	Action	Probability	Fallback
M0 (now)	Requisition open; active recruitment	—	—
M3	Target hire date	40%	Engage consultant (€45k, 0.3 FTE)
M6	Extended recruitment window	65% cumulative	Promote internal + accelerate docs
M9	Final window	75% cumulative	Accept bus factor = 1; retention bonus

Accepted risk: If shadow hire unfilled by M9, programme continues with bus factor = 1 and increased retention bonus (€25k vs. €15k). This is accepted risk, not programme termination.

8.2 Training Timeline (Industry Benchmarked)

Role	This Programme	Typical Fab	Gap Analysis
Basic operator	2 weeks	4-8 weeks	Acceptable — tool is simpler
Recipe modifier	8 weeks + exam	3-6 months	Extended from 4 weeks
Process engineer	3 months	6-12 months	Gap — requires Phase 2 programme

9. Fabrication Integration

9.1 MES Interface Testing — Phase 1 Scope

Full SEMI E30 certification is Phase 2. However, Phase 1 includes interface testing milestones:

- M6 deliverable: JSON recipe interface tested against simulated MES host
- M12 deliverable: SECS-II message exchange validated with test harness
- M18 deliverable: Integration test report documenting AOI → Electrospray → Verification data flow

Exit criterion: Phase 1 exit criteria include successful interface test with at least one customer AOI system (dirty data handling validated).

9.2 AOI Dirty Data Handling

AOI Variation	Handling	Phase 1 Action
Image format (TIFF/PNG/BMP)	Format normalisation layer	Support all three; test each
Resolution (0.5-2 μm/pixel)	Resampling to 1 μm/pixel	Validate accuracy post-resample
Coordinate system (varies)	Transform to machine coordinates	Calibration procedure documented
Defect classification schema	Map to internal categories	Mapping table per AOI vendor

10. AI Classification System

10.1 Architecture

- Model: ResNet-50 backbone, three-class output (REPAIRABLE, SCRAP, UNCERTAIN)
- Input: AOI images (2048×2048 px)
- Framework: PyTorch 2.x → ONNX runtime

10.2 Explainability Features

Feature Category	Example Output	Meaning
Defect geometry	"Linear discontinuity, 12 μm length"	Shape and size of detected anomaly
Location context	"Adjacent to via, 3 μm clearance"	Proximity to critical structures
Severity indicator	"Resistance impact: HIGH (open)"	Estimated electrical consequence
Confidence driver	"High edge contrast (0.87)"	Why model is confident/uncertain

Features are human-readable descriptions, not pixel coordinates. Operator training includes a 2-hour feature interpretation module.

10.3 Training Data and Domain Shift

Factor	Training Data	Deployment	Risk	Mitigation
Process node	7-28 nm	14-45 nm	MEDIUM	Fine-tuning
Defect distribution	ASE mix	Customer-specific	HIGH	500-1000 labelled images
AOI equipment	ASE standard	Variable	MEDIUM	Image normalisation

10.4 Customer Data Acquisition

Training data acquisition is secured via binding pilot agreement: Customer provides 1,000 labelled defect images within 60 days of equipment installation. Labels include REPAIRABLE (with repair outcome), SCRAP (with reason), and UNCERTAIN. In exchange, customer receives 6-month free tool usage during pilot and 20% discount on production purchase. Data ownership remains with customer; programme receives perpetual license for model training. Backup pilot LOI in place if primary customer withdraws.

10.5 Human Override Protocol

AI Output	Confidence	Human Authority	Audit
REPAIRABLE	≥85%	Approve or override	Override logged
REPAIRABLE	<85%	Must review	Review logged
SCRAP	≥90%	Approve or escalate	Escalation logged
SCRAP	<90%	May override	Justification required
UNCERTAIN	Any	Human decides	Rationale required

10.6 Automatic Retraining with Human Approval

- Early warning: Override rate >10% for 3 days triggers automatic model pause; PROCESS_ENGINEER approval required to resume
- Distribution drift: KL divergence >0.1 flags for review; PROCESS_ENGINEER approves fine-tuning

- Circuit breaker: Override rate >20% disables model; human-only mode; retraining requires ADMIN + independent certifier approval

Time-critical override: ADMIN can enable "emergency human-only mode" which bypasses AI entirely (not re-enables failed model). This is fail-safe, not fail-open. Emergency mode logged; requires incident review within 24 hours.

10.7 Access Control Matrix

Role	View	Run	Modify	Create	Bypass
BASIC_OPERATOR	✓	✓	✗	✗	✗
RECIPE_MODIFIER	✓	✓	✓	✗	✗
PROCESS_ENGINEER	✓	✓	✓	✓	✗
ADMIN	✓	✓	✓	✓	✓*

**ADMIN bypass requires incident report reviewed by independent party within 48 hours. Unreviewed bypasses trigger automatic escalation.*

11. Procurement Analysis

11.1 zeroK Term Sheet (Executed)

Term	Value	Status
Price	€920k fixed	AGREED
Escalation cap	8% annual, 3 years	AGREED
Lead time	20 months from deposit	AGREED
Deposit	€50k refundable if cancelled by M6	AGREED
Performance	Resolution <15 nm or refund	AGREED
Exit	Full refund if acceptance fails	AGREED

Reference: zeroK-RCC-TS-2025-001 executed 15 January 2025.

11.2 M6 Decision Logic

M6 Result	Root Cause	Decision
<5 μm	Success	Continue Electrospray; defer LoTIS
5-10 μm, correctable	Stage/substrate issue	60-day sprint; hold LoTIS
5-10 μm, fundamental	Physics limit	Confirm LoTIS; Electrospray fallback
>10 μm	Any	Confirm LoTIS; evaluate termination

11.3 LoTIS Capability Gap Bridging Plan

If pivot to LoTIS is triggered at M6, there is a 17-month gap until LoTIS delivery (M23). The bridging plan maintains programme value during this period:

Period	Activity	Value Delivered
M6-M9	Complete Electrospray characterisation for fallback applications	Publications; deposition database
M9-M12	Develop Electrospray for MEMS/sensor (5-20 μm) market	Pivot to larger-pitch applications
M12-M18	Process documentation; seek licensing partner for coatings	IP value recovery
M18-M23	LoTIS installation planning; facility prep	Readiness for LoTIS
M23+	LoTIS commissioning; recipe development	Primary capability restored

True worst case: If both Electrospray (for primary market) AND LoTIS pivot fail, programme terminates with €145-220k asset recovery.

12. Software Supply Chain Security

12.1 Software Bill of Materials (SBOM)

SBOM maintained in CycloneDX format, updated with each dependency change:

Component	Version	License	CVE Check
PyTorch	2.1.x	BSD-3-Clause	Weekly scan
ONNX Runtime	1.16.x	MIT	Weekly scan
NumPy	1.26.x	BSD-3-Clause	Weekly scan
OpenCV	4.8.x	Apache-2.0	Weekly scan
PostgreSQL driver	psycopg2 2.9.x	LGPL	Weekly scan

12.2 Vulnerability Management

- Scanning tools: Dependabot + Snyk
- Frequency: Weekly automated; manual review for CRITICAL/HIGH
- Remediation SLA: CRITICAL 24 hours; HIGH 7 days; MEDIUM 30 days; LOW next release
- Exception process: Document in risk register; implement compensating control

12.3 Dependency Pinning

- All dependencies pinned to specific versions (not ranges)
- Hash verification for all packages (pip --require-hashes)
- Private PyPI mirror for approved packages

13. Fragility Assessment

External assessment established fragility at 78% (22% success probability). This is accepted as the authoritative estimate.

Factor	Assessment	Notes
Single architecture	+5%	Unchanged
No prototype	+20%	Unchanged
Bus factor	+6%	Increased (shadow hire risk)
Fab integration	+6%	Unchanged
Pivot procurement	+3%	Term sheet mitigates
Market	+5%	Unchanged
Regulatory	+3%	Data sovereignty resolved
Unit economics	+8%	J-curve acknowledged
AI classification	+7%	Customer data dependency
Laser procurement	+5%	Unchanged
Shadow hire execution	+6%	Increased
Capability gap	+4%	NEW: LoTIS gap risk
TOTAL	**78%**	—

78% fragility (22% success probability) is consistent with budget-comparable reference class programmes showing approximately 25% commercial success rate. The programme is high-risk but appropriately sized for exploration. Pre-registration via Zenodo DOI; external author will write retrospective; raw data published regardless of outcome.

14. Intermediate Deliverables

Month	Deliverable	Standalone Value	Risk
3	Electrospray characterisation	Publishable	LOW (20%)
6	Deposition database (Au/Ag/Cu)	Licensable IP	MEDIUM (40%)
9	Sintering dose-response	Publishable	MEDIUM (35%)
12	Integrated system	Demonstrable	HIGH (55%)
15	Wetting study	PhD thesis	MEDIUM (40%)
18-20	Go/No-Go report	Decision support	LOW (25%)

14.1 Worst-Case Recovery

Asset	Value	Path
Equipment	€80k	Resale
Laser	€40-60k	Resale
IP + documentation	€25-80k	Licensing
Publications	Reputational	Academic
TOTAL	**€145-220k (22-33%)**	—

15. Recommendations

15.1 Primary Recommendation: Proceed to Phase 1

All pre-conditions satisfied. All stakeholders at FULL GO. Phase 1 authorised:

1. €670,000 envelope (€550k commitment + €120k contingency)
2. 20-month timeline with gates at M6, M12, M18
3. Shadow hire requisition open; fallback plan in place
4. Customer pilot LOI executed for data acquisition
5. zeroK term sheet executed; deposit at M3
6. LoTIS capability gap bridging plan defined

15.2 Go/No-Go Criteria

Gate	GO	CONDITIONAL	NO-GO
M6	<5 μm (Au)	5-10 μm correctable	>10 μm
M12	Continuous joints; HAZ <1 μm	HAZ 1-1.5 μm	HAZ >2 μm
M18-20	Electrical + adhesion pass	Marginal adhesion	Reliability <100 hr

15.3 Do Not Proceed

- Atomic Fountain or Plasma Bridge development
- Patent claims for sub-100 nm Electrospray precision
- AI deployment before independent certification
- Recipe modification without RECIPE_MODIFIER role
- ADMIN bypass without 48-hour independent review

16. Conclusion

This feasibility analysis resolves all blocking issues identified through comprehensive technical review. The programme addresses lifecycle cost modelling with a 5-year TCO of €2.88M cumulative and clear breakeven analysis. Customer data acquisition is secured through binding pilot agreement with 1,000 labelled images contractually required. Tail latency is characterised through P99 analysis with 10% schedule buffer. Supply chain security is addressed through SBOM policy with weekly vulnerability scanning. The capability gap risk is mitigated through a 17-month bridging plan with continued Electrospray development for fallback markets.

The programme remains high-risk at 78% fragility, but this is appropriate for exploratory R&D at €670k scale. Risk is characterised, bounded, externally validated, and mitigated. All five stakeholders approve.

PROGRAMME STATUS: FULL GO. Phase 1 is authorised to proceed.

Appendix A: Document Metadata

Field	Value
Document Title	Pico-Scale Welding: Feasibility Analysis and Architecture Down-Selection
Subtitle	Nanoscale Material Joining for FOWLP RDL Repair
GUID	AG-2025-0104-5562
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Author	Aaron Garcia
Affiliation	Independent Researcher
Contact	aaron@garcia.ltd
Origin Context	Technical feasibility study following comprehensive red team analysis
Status	APPROVED FOR PHASE 1
Fragility Assessment	78% (externally assessed)
Budget	€670,000 envelope
Timeline	20 months

Appendix B: Glossary

Term	Definition
AOI	Automated Optical Inspection
DPA	Data Processing Agreement
FIBID	Focused Ion Beam Induced Deposition
FOWLP	Fan-Out Wafer-Level Packaging
FTE	Full-Time Equivalent
HAZ	Heat-Affected Zone
LOI	Letter of Intent
LoTIS	Low-Temperature Ion Source (alternative architecture)
MES	Manufacturing Execution System
ONNX	Open Neural Network Exchange
PI	Professional Indemnity (insurance)
RDL	Redistribution Layer
SAM	Serviceable Addressable Market
SBOM	Software Bill of Materials
SECS-II	SEMI Equipment Communications Standard
TCO	Total Cost of Ownership
TTM	Two-Temperature Model
UHV	Ultra-High Vacuum

Appendix C: Methodology and Transparency Statement

Author Context & Expertise

This work is grounded in 30 years of multi-sector experience in Systems Engineering. The analytical framework reflects professional history, focusing on practical application.

Digital Methodology & Accessibility

In the spirit of transparency, I utilised a suite of Generative AI tools—specifically Claude, Google Gemini, and ChatGPT—to assist in the production of this paper. These tools were employed as "force multipliers" for data synthesis and editorial accessibility. As a writer with dyslexia, I leverage these models as assistive technology to refine grammar and streamline sentence structure.

Verification & Integrity

While AI assisted in processing data, the intellectual oversight is entirely human. I performed manual validation of all citations and accept full responsibility for the accuracy and originality of the final output.

Appendix D: Executed Agreements Summary

Document	Reference	Date	Key Terms
zeroK Term Sheet	zeroK-RCC-TS-2025-001	15 Jan 2025	€920k; 8% cap; 20-mo delivery
zeroK Queue Confirmation	Email Exhibit	12 Jan 2025	€50k reserves 6-month slot
ASE DPA	ASE-RCC-DPA-2025-001	10 Jan 2025	50k images; EU hosting
Customer A Pilot LOI	PILOT-RCC-2025-001	18 Jan 2025	1,000 labelled images; 6-mo pilot
Customer B Backup LOI	PILOT-RCC-2025-002	20 Jan 2025	Backup if Customer A withdraws
Shadow Hire Requisition	REQ-2025-017	08 Jan 2025	0.5 FTE; M0 open

Appendix E: Customer Pilot Agreement Summary

Full agreement: PILOT-RCC-2025-001 (confidential; available under NDA).

Key Terms:

- Customer provides 1,000 labelled defect images within 60 days of installation
- Labels: REPAIRABLE (with repair outcome), SCRAP (with reason), UNCERTAIN
- Image format: TIFF, 2048×2048, 8-bit grayscale
- Programme receives perpetual, non-exclusive license for model training
- Customer retains data ownership; can request deletion (except trained model weights)
- Programme provides 6-month free tool usage during pilot
- Customer receives 20% discount on production unit if pilot successful
- Either party can terminate with 30 days notice; data license survives termination