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Post-processing of CEPC SC cavities: review and outlook for mass production

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A review of the post-processing routes already qualified for CEPC cavities, followed by an assessment of their suitability for the two-year processing window and a prioritised work list.

Order of the review

The 1.3 GHz route is presented first because it is qualified; the 650 MHz route follows as the open decision it still is.

01 **Background and the mass-production challenge**
Higgs 30 MW configuration, acceptance specifications, the 26-month window, the PAPS facility

02 **Post-processing routes: one qualified, one to be decided**
1.3 GHz EP + mid-T baking, verified to cryomodule; the two 650 MHz candidates and their evidence

03 **Scale-up to mass production**
Benchmarks, yield and failure modes, cost and cycle-time drivers, process capability

04 **Outlook**
Cross-industry lessons, the prioritised work packages and conclusions

01

Background and the mass-production challenge

The CEPC SRF system in the 30 MW Higgs mode, the acceptance specifications for both cavity families, the processing window left by the schedule, and the facility that has to deliver it.

192 × 650 MHz 2-cell

96 × 1.3 GHz 9-cell

≈ 2-year processing window

01 Acceptance specifications for the two cavity families

What each family must deliver

Item	650 MHz 2-cell (collider)	1.3 GHz 9-cell (booster)
Vertical-test acceptance	Eacc ≥ 30 MV/m; Q0 ≥ 3.6×10^{10} @ 25 MV/m	Eacc ≥ 24 MV/m; Q0 ≥ 3.0×10^{10} @ 22 MV/m
Module acceptance	Eacc ≥ 28 MV/m; Q0 ≥ 3.3×10^{10} @ 25 MV/m	Eacc ≥ 22 MV/m; Q0 ≥ 3.0×10^{10} @ 22 MV/m
Long-term operation	28 MV/m; Q0 = 3.0×10^{10} @ 25 MV/m	≈ 21.8 MV/m; Q0 = 3.0×10^{10} (CW)
Operating temperature	2.0 K	2.0 K
Process demand	**High gradient and high Q0 together**	High Q0, moderate gradient

Three tiers of acceptance

The **vertical test** at 2 K decides whether a cavity is accepted at all; the **module test** decides whether the string keeps it; **long-term operation** is the number the cryoplant is actually sized on.

650 MHz is the demanding line

It asks for a higher gradient and a higher Q0 than the 1.3 GHz family — 30 MV/m with 3.6×10^{10}, against 24 MV/m with 3.0×10^{10}. Two thirds of the fleet sits on this harder line.

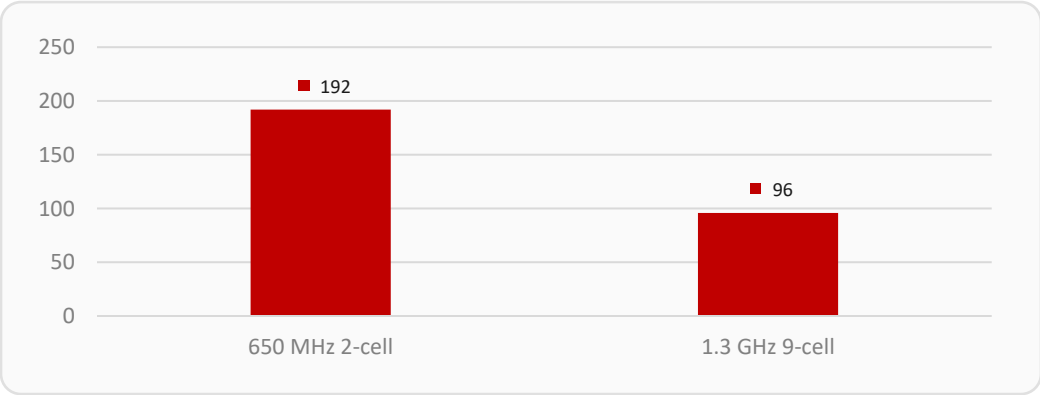
So what?

Both numbers must hold on the same cavity in the same test. That single sentence is what turns a surface recipe into a production problem.

01 How many, and how fast: 288 cavities in 26 months

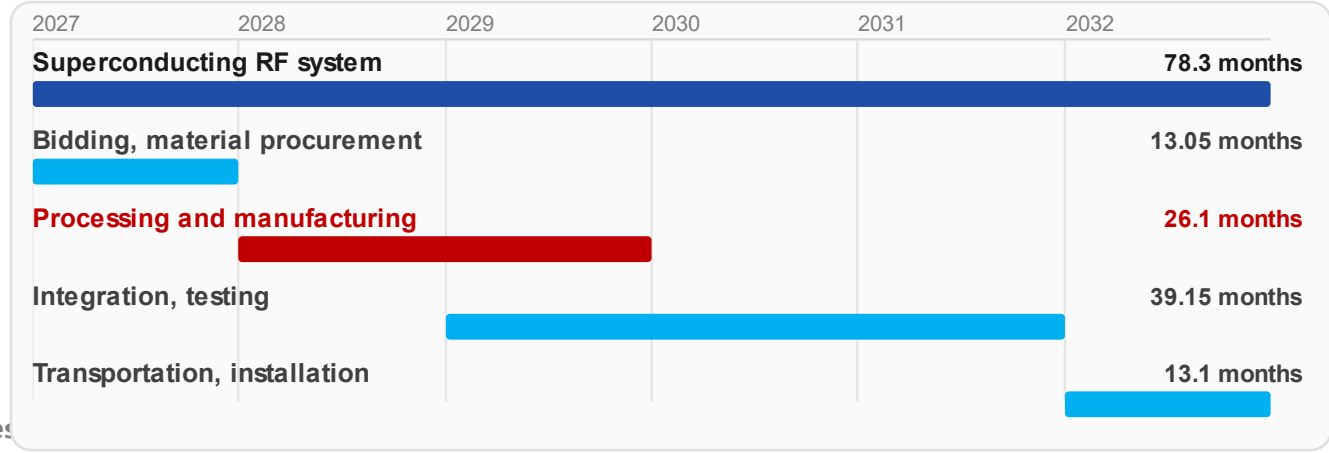
The Higgs 30 MW fleet is **288 cavities in 44 cryomodules**, and the SRF-system schedule gives the processing and manufacturing phase **26.1 months — about two years**. Both numbers together, not the annual cavity count alone, define the rate the line has to hold.

Cavities to process, by family



32 cryomodules of six 650 MHz cavities + 12 cryomodules of eight 1.3 GHz cavities

The same schedule as a timeline



288

192 × 650 MHz 2-cell + 96 × 1.3 GHz 9-cell, in 44 cryomodules

26.1 months

available for processing and manufacturing (2028/1 – 2029/12)

≈ 144 / year

accepted cavities the phase has to deliver — about 12 a month

The catch: 144 a year is what has to be **accepted**, not what has to be **processed**. With a yield below 100 %, the line has to run more cavities than it delivers — and the window does not stretch to absorb the difference. That gap is quantified on p.8.

01 The PAPS SRF facility: the platform that will do it

Cavity post-processing, cryogenic test and cryomodule integration are planned at the SRF facility of the **Platform of Advanced Photon Source Technology R&D (PAPS) in the Huairou Science City, Beijing** — directly opposite the High Energy Photon Source and in operation since 2021. **It was built from the outset with the mission of supporting series production**, not only single-cavity research.

4 500 m²
dedicated SRF area for post-processing, cryogenic test and integration

200 / year
processing capacity — cavities through surface treatment and test

12–20 / year
cryomodules assembled and horizontally tested

2.5 kW / 300 W
refrigeration at 4.5 K and 2 K, down to 1.4 K

Vertical test area
Three dewars (two of ID 1.25 m, one of ID 0.8 m for R&D), two-layer magnetic shielding, T-mapping for 650 MHz 2-cell and 1.3 GHz 9-cell; 8–10 nine-cell tests per week.

Vacuum furnaces
Furnace for nitrogen doping, annealing and furnace baking; separate 1 200 °C furnace for Nb_3Sn coating.

Horizontal test area
Two caves with a test cryomodule for the horizontal test of cavity, coupler and tuner assemblies.

RF power and low-level RF
Solid-state amplifiers at 166.25, 325, 500 and 650 MHz and at 1.3 GHz, with the associated LLRF and interlock chains.

Clean room
500 m² for high-pressure rinsing, ultrasonic and ultrapure-water cleaning, and cavity-string and coupler assembly.

Optical inspection
Automated inspection with grinding of the equator and iris regions — the metrology that makes a surface step reproducible.

Electropolishing and pure water
Horizontal EP system at co-building base in Ningxia， with acid handling, chilling and waste treatment; compatible with 650 MHz up to 5-cell and 1.3 GHz up to 9-cell.

Pre-tuning
Pre-tuning and coaxiality measurement developed with Peking University; field flatness is set before the string is assembled.

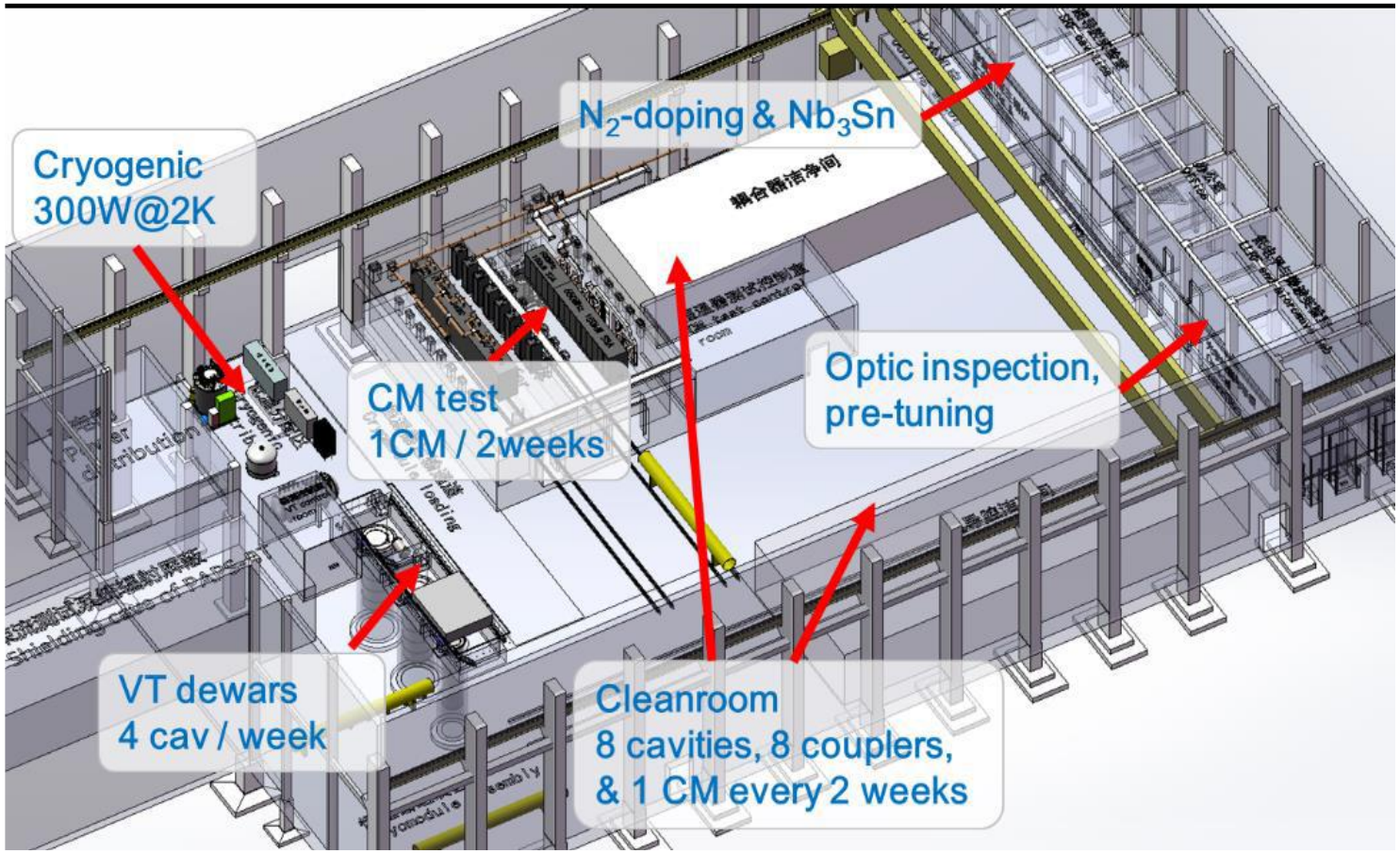
PAPS (1)

- The SRF facility has been developed at Platform of Advanced Photon Source Technology R&D (PAPS), which is just close to the High Energy Photon Source (HEPS).





PAPS (2)





Area: 4500 m^2
Capacity: 200 SRF cavities / year (post process, cryogenic test and integration, etc).

PAPS (3)



RF power source: solid state amplifier (162.5/325/500/650 MHz, 1.3 GHz)





Clean room



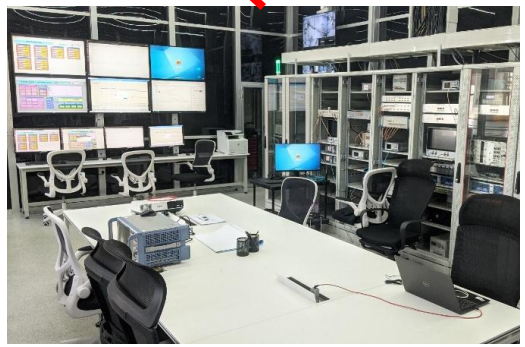
Vertical test stand



Horizontal test stand



furnace

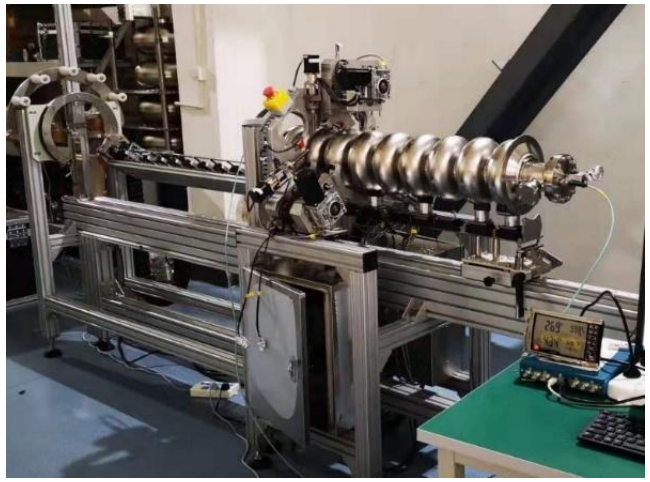


Low-level RF

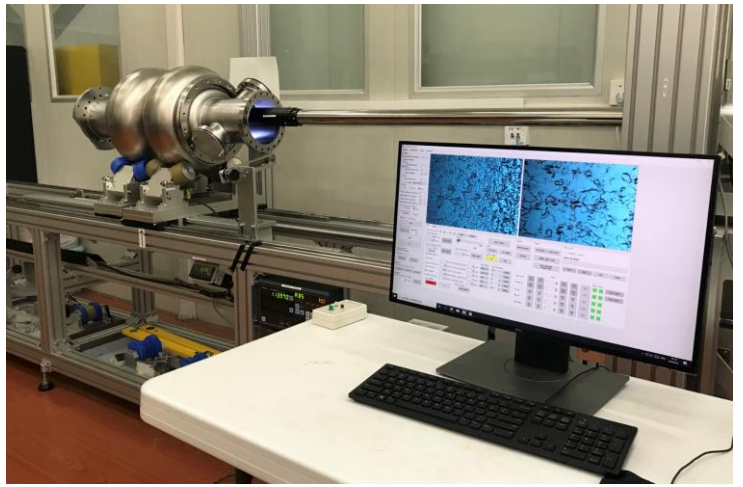
PAPS (4)



Vacuum furnace: Nitrogen doping, annealing, baking



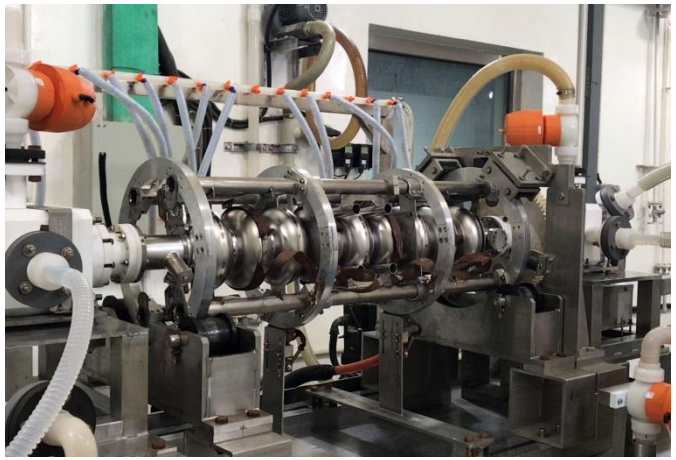
Pre-tuning of 1.3 GHz 9-cell cavity



Optical inspection



Vertical test Dewar



Electro-polishing at Ningxia



Pure water system



Furnace for Nb3Sn coating



Vertical test of SRF cavities

01 Confidence from the record: what PAPS already delivers

300+
cavity vertical tests completed since 2021

20+
horizontal tests of cavity and coupler assemblies

300+
clean-room assemblies and high-pressure rinse runs

50+
furnace runs — nitrogen doping and mid-T bake

DELIVERED • 5 JUNE 2023

The world's first 1.3 GHz cryomodule with eight mid-T baked 9-cell cavities

China's first high-Q 1.3 GHz 9-cell accelerating cryomodule: eight mid-T baked cavities, assembled and commissioned as a complete unit. Measured in the horizontal test: **193.5 MV total CW voltage**, average usable gradient **23.3 MV/m** and average **Q0 = 3.6×10¹⁰ at 21 MV/m**. Total 2 K heat load 83.5 W at 133 MV and 133 W at 173 MV.*

What it proves: mid-T performance survives helium-vessel welding, string assembly and cryomodule integration — the stage where laboratory results usually degrade.

Mid-T baking has since been **adopted for SHINE and PIP-II** and will be used for CEPC — the route is no longer a laboratory proposal.

Pan, W., et al. (2024). Phys. Rev. Accel. Beams 27, 092003.

DELIVERED • BEYOND THE 1.3 GHz MODULE

Cryomodules already built and tested

PAPS has delivered the high-Q 1.3 GHz module and the light-source modules, including the 166 MHz and 500 MHz modules for HEPS, the 500 MHz module for the Hefei Advanced Light Source (HALF), the 1.5 GHz module, part of the 324 MHz modules for CSNS-II, and the superconducting module for the BEPC-II upgrade.

INDUSTRIAL PARTNERS

Cavities built by industry, no failed unit

The 1.3 GHz 9-cell cavities in the mid-T cryomodule were produced with industrial partners with no failed cavity — the supply chain for niobium cavities exists and is qualified.

01 The challenge: capacity is sufficient, the yield margin is not

1 • The acceptance is coupled

Q0 and gradient depend on different parts of the surface. Optimizing one can break the other, and the damage only appears at the end of the chain, after the costly steps are spent.

2 • Yield loss is inherent

SHINE's 252 dressed cavities*: 60 % pass as received, 76 % qualified after HPR or retest, 14 % concession, 10 % unqualified. Five surface steps at 95 % each give $0.95^5 \approx 77$ % — the arithmetic of a chain, not of a bad vendor.

3 • The window does not stretch

26.1 months is fixed. A rework loop does not add time to the schedule — it consumes the same two years, on the same EP, furnace and test slots.

The arithmetic of the window

Cavities to be accepted	**288**
÷ 76 % qualified yield → to be processed	**≈ 380**
Slots in the window (200 / year × 2.17)	**≈ 435**
First pass alone takes	**87 %**
Adding rework (10–24 %)	**96–108 %**

0–4 % margin once rework is counted

So the challenge is not capacity — it is capability. Prefer the route with the fewest, most reproducible unit operations, not the one with the highest laboratory Q0: fewer steps mean fewer defect opportunities, a shorter cycle time and a lower cost per accepted cavity. And control has to sit upstream, on the surface steps — there is no room to discover a problem at the test stand.

* Chen, J., Cao, S., Gong, L., et al. (2025). Status of SRF activities for the SHINE project. SRF2025, MOB04 (JACoW).

02

Post-processing routes: one qualified, one to be decided

The 1.3 GHz 9-cell route is already qualified at IHEP and adopted for the booster; the 650 MHz 2-cell route has two candidates that differ only in how the damage layer is removed.

- 1.3 GHz: EP + mid-T baking
- 650 MHz: candidates A and B
- mid-T baking common to both

02 Two cavity families, two maturity levels

The two cavity families are at different stages. The 1.3 GHz 9-cell route is **already qualified and verified up to the cryomodule**, so it can be taken as settled. The 650 MHz 2-cell route is **still pre-series**: two candidate sequences are on the table and the choice has to come from 2-cell prototype measurements.

FAMILY 1

1.3 GHz 9-cell

96 cavities · 12 cryomodules · booster ring

ROUTE QUALIFIED

EP + mid-T baking — one chemical step, no light EP

Bulk EP	Annealing	Air exposure	Mid-T bake	HPR + assembly	Vertical test
180 µm @ 25 °C	900 °C / 3 h	≥ 2 days, clean room	300 °C / 3 h	clean room	then cryomodule

FAMILY 2

650 MHz 2-cell

192 cavities · 32 cryomodules · collider ring

TWO CANDIDATES

A	Bulk EP 180 µm @ 25 °C	Annealing 900 °C / 3 h	Clean assembly clean room	Mid-T bake 300 °C / 3 h	HPR · vertical test then module
B	BCP ≈ 180 µm	Light EP 20 µm	Annealing 950 °C / 3 h	Clean assembly clean room	Mid-T bake 300 °C / 3 h	HPR · vertical test then module

Same finish, different polishing. All three sequences end in the same mid-T bake, so they inherit the same Q0 benefit. They differ only in how the 180 µm damaged layer is removed — and that is where cost, cycle time and the quench field are decided.

02 1.3 GHz 9-cell: EP + mid-T baking is the adopted route

The settled process chain for the 96 booster cavities

Bulk EP → anneal → air exposure → mid-T bake

1 EP

Bulk EP 180 µm (25 °C) → annealing 900 °C / 3 h → exposure to air → **mid-T furnace bake 300 °C / 3 h**. IHEP simplified the procedure to **a single bulk EP**: no light EP, no nitrogen, no 120 °C low-temperature bake (Pan et al. 2024).

Twelve mid-T 9-cell cavities were vertically tested: average gradient **26 MV/m**, average **Q0 = 4.5×10¹⁰ at 16–23 MV/m**, best cavity 31.3 MV/m. Fourteen mid-T 9-cell cavities have been tested in total.

EP baseline — what it replaced

The same chain ending in a 75 °C / 120 °C low-temperature bake, and needing two EP steps instead of one. Q0 stayed around 1.5–2×10¹⁰ (He et al. 2021).

Nitrogen doping — the alternative

It reaches 3.0×10¹⁰ at 21 MV/m but needs three to four EP steps plus a post-doping light EP (Gonnella 2018).

Why the route is fixed: mid-T baking needs one EP instead of three, and the bake has succeeded on every IHEP cavity tested; its industry adoption is shown earlier. For CEPC it is the route for the 1.3 GHz booster cavities, and the verified performance is reproduced on the right.

Vertical-test evidence

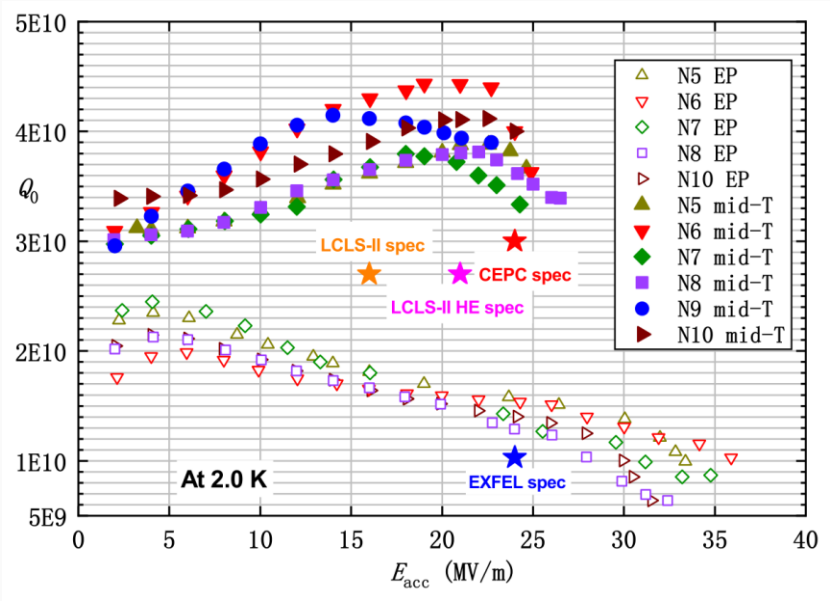


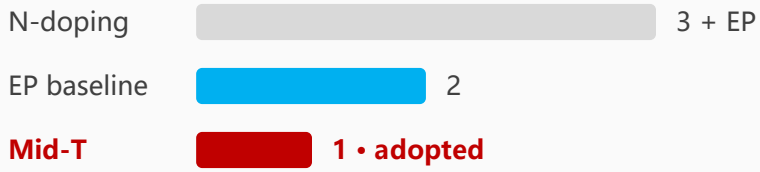
Fig. 10 of He et al. (2021): Q0 versus accelerating gradient at 2.0 K for the six 1.3 GHz 9-cell cavities. Solid markers are after mid-T furnace baking, hollow markers are the EP baseline. The LCLS-II, LCLS-II-HE and CEPC specification points are marked on the plot.

Note the **anti-Q-slope**: Q0 rises with field for the mid-T cavities — the signature the route is traded on, and the reason the EP baseline cannot meet the specification.

02 The simplification is the saving: one EP step

Mid-T baking needs **one chemical step** where the EP baseline needs two and nitrogen doping three or four. At 96 booster cavities that is not a detail of chemistry — it is the largest single lever on cost, cycle time and surface-defect risk.

Chemical (EP) steps per cavity



Why one step is enough — the evidence

N9 skipped the light EP after the 900 °C anneal and still matched N5–N8 within scatter: the high-temperature contamination stays acceptable, so the second polish buys nothing (He et al. 2021).

What one fewer step takes off the line

- acid handling
- chilling
- ultrapure rinse
- waste treatment

Each step is a full 180 µm removal, and all of it runs on the same EP line the 650 MHz cavities are queued for — a step removed is a step returned to the other family.

What one step is worth

One EP run is ≈ CNY 80k per 9-cell cavity, so dropping one run saves **≈ CNY 7.7M** across the 96 booster cavities.

What it frees

Ninety-six EP slots returned to the 650 MHz programme on the same line, plus the acid and waste handling that goes with every run.

The same trade decides the 650 MHz route: candidate A reaches mid-T with one bulk EP, candidate B with BCP plus a light EP. Counting unit operations, not laboratory Q0, is the way to choose between them.

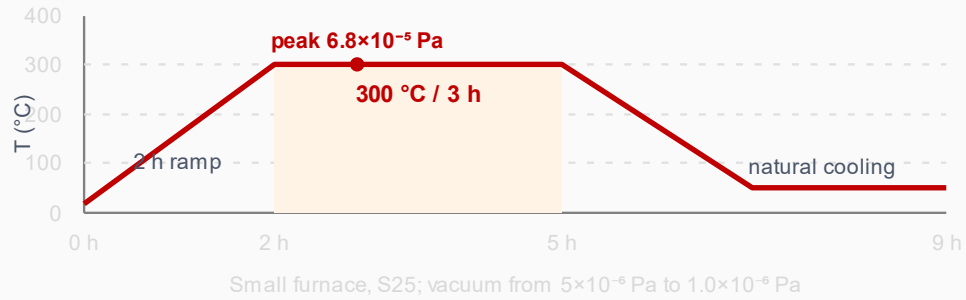
02 Mid-T bake: process window, vacuum and RGA

What the furnace recipe specifies

Parameter	Specified value
Baking temperature	225 – 400 °C window; 300 °C optimum
Hold time	3 h at set point
Ramp / cooling	2 h ramp-up; natural cooling to 50 °C
Base pressure	< 5×10^{-6} Pa (cryopumped, dual-chamber furnace)
Peak pressure at 300 °C	6.8×10^{-5} Pa (small) · 2.4×10^{-5} Pa (large furnace)
Pressure after cooling	1.0×10^{-6} Pa (small) · 2.8×10^{-6} Pa (large)
Furnace charging	Nb holders; flanges covered with Nb foil
Post-bake	HPR + clean assembly; no 120 °C bake

Source: He et al. (2021); Sha et al. (2022).

Typical temperature profile



Small furnace, S25; vacuum from 5×10^{-6} Pa to 1.0×10^{-6} Pa

Residual-gas species monitored (RGA, m/z)

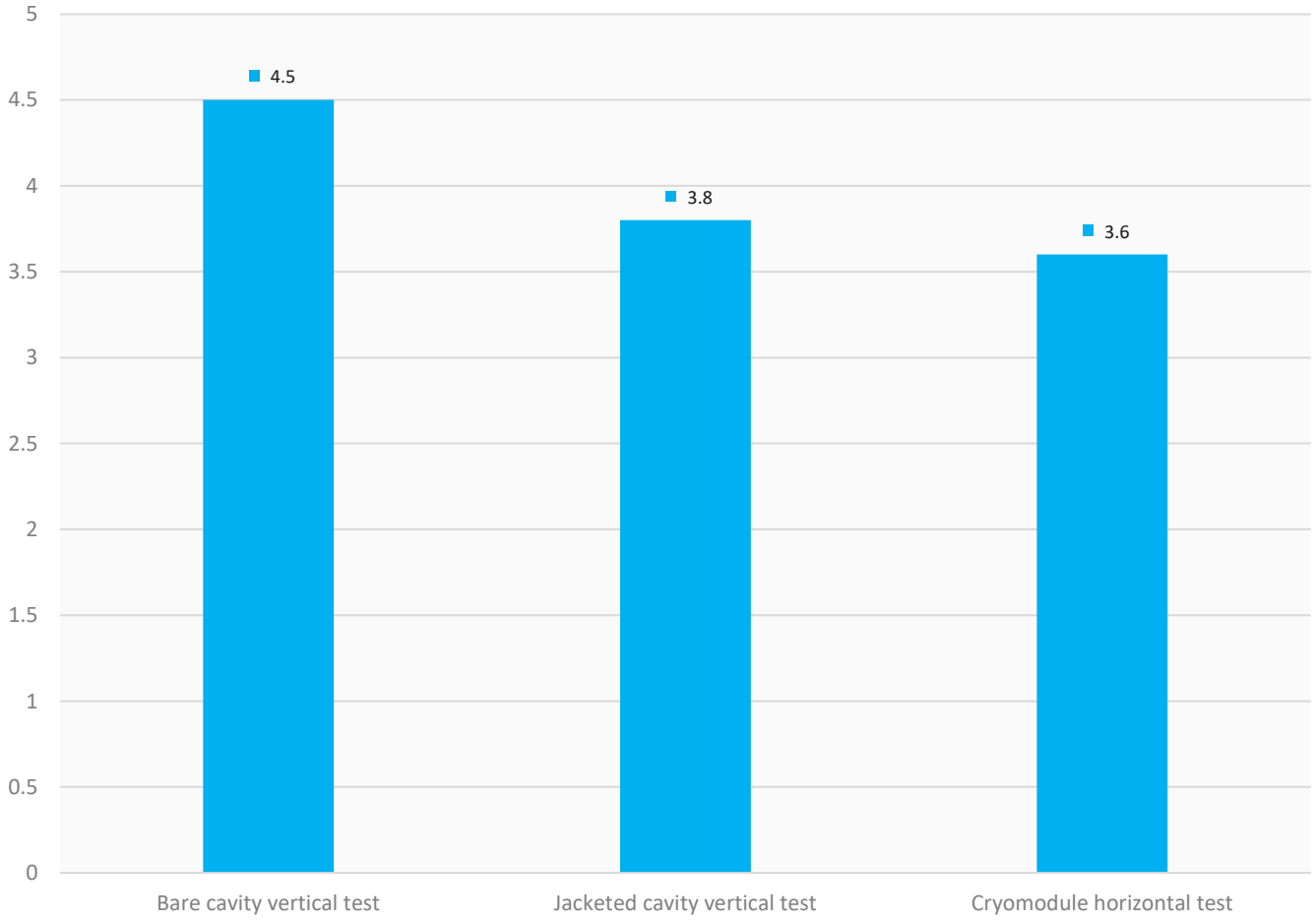
H_2 • 2 | H_2O • 18 | N_2 • 28 | O_2 • 32 | Ar • 40 | CO_2 • 44

So what? The temperature window is wide — ±50 °C around 300 °C still yields high Q0 — so the recipe is not the hard part. Repeatability comes from furnace cleanliness and pumping speed: CO_2 was higher in the new large furnace and is expected to fall as the furnace ages.

02 Mid-T bake: verification chain to the cryomodule

Q0 at 16 MV/m, from bare cavity to module

average of 8 cavities · Q0 in 10^{10}



Bare values are from 12 mid-T 9-cell cavities; the module average is derived from the measured total 2 K dynamic heat load and validated against individual cavity measurements (He et al. 2021; Pan et al. 2024).

What the module actually delivered

193.5
MV total CW rf voltage, 8 cavities

23.3
MV/m average usable gradient (spec > 23)

0.08
mSv/h max dose at 16 MV/m (spec 0.5)

12 h
continuous operation at 133 MV, no trip

2 K heat load / stage

83.5 W at 133 MV sits inside the DALS (130 W), LCLS-II / SHINE (93 W) and LCLS-II-HE (137 W) envelopes; at 173 MV the load rises to 133 W, inside LCLS-II-HE (137 W) but above the DALS and LCLS-II / SHINE values.

So what? The mid-T gain survives helium-vessel welding and module assembly: Q0 falls only ~20 % from bare cavity to module, and the usable gradient stays above the CEPC requirement.

02 Mid-T bake: consolidated learnings

Six process facts established on 1.3 GHz 1-cell and 9-cell cavities — each one directly affects how the route will behave on a few hundred units.

TIME

Air exposure ≥ 2 days

Two days in a clean room gives Q0 = 3.5–4.4×10^{10}. Just 1.5 h (N6) or 5 min (N9) left Q0 below 3.0×10^{10} with quench under 30 MV/m; a second bake recovered both. The optimum is still under study.

STEPS

Light EP can be omitted

N9 received only bulk EP (160 µm + 20 µm) with no light EP and matched the cavities that had one. Removing the step deletes a chemical operation, its rinse and its waste stream.

AVOID

Low-T bake is unfavourable

The 120 °C / 48 h bake normally used before high-pressure rinsing slightly lowered Q0 on mid-T cavities (S21, S18). It must be left out of the recipe, unlike in the EP baseline route.

YIELD

Jacketing is safe

Helium-vessel welding (N6, N9) degraded neither Q0 nor Eacc, so the treatment is compatible with the standard module integration sequence without an extra recovery step.

ROBUSTNESS

Survives re-exposure

Four months of clean-room air exposure followed by another HPR left Q0 and gradient essentially unchanged — an important tolerance for a production line with buffer storage.

TRACK RECORD

100 % success to date

Fourteen mid-T 9-cell cavities have been processed by industrial vendors with no failures (Pan et al. 2024; Sha 2026).

Taken together: the 1.3 GHz mid-T furnace baking route is a low-risk, already-verified baseline for the booster cavities — and the natural template to test at 650 MHz.

02 650 MHz: two candidate routes on the table

Both candidates share the mid-T bake; only the polishing sequence differs

Candidate A — bulk EP + mid-T bake

1 EP

Bulk EP → annealing 900 °C / 3 h → exposure to air 48 h → clean-room assembly → mid-T bake 300 °C / 3 h → HPR. No light EP after the bake.

Not yet run on a 650 MHz cavity: no measurement exists for this sequence. The first trial sits in the near-term work packages (p. 30).

Candidate B — BCP + light EP + mid-T bake

BCP + 1 EP

Bulk BCP → 950 °C / 3 h anneal → light EP → clean-room assembly → mid-T bake 300 °C / 3 h → HPR.

Light EP after BCP unlocks the gradient: BCP alone quenches at ≤ 23 MV/m, but light EP reaches 35 / 37.5 MV/m — 650S4 already meets both lines without the bake. After mid-T the quench falls to 24.2 / 31.2 MV/m (Jin et al. 2021; Sha et al. 2022).

Why both stay open

The 650 MHz programme is still pre-series — the first 2-cell cavity is in post-processing and the others are under electron-beam welding (Sha 2026). Only the BCP + light EP chain has 1-cell evidence; the bulk-EP route is a simplification with no run yet.

What is at stake: the two acceptance numbers, surface finish (BCP is rougher) and fixture cost (EP needs a cathode). The measured mid-T quench drop — **24.2 / 31.2 MV/m** — is the piece still unresolved (p. 21–22).

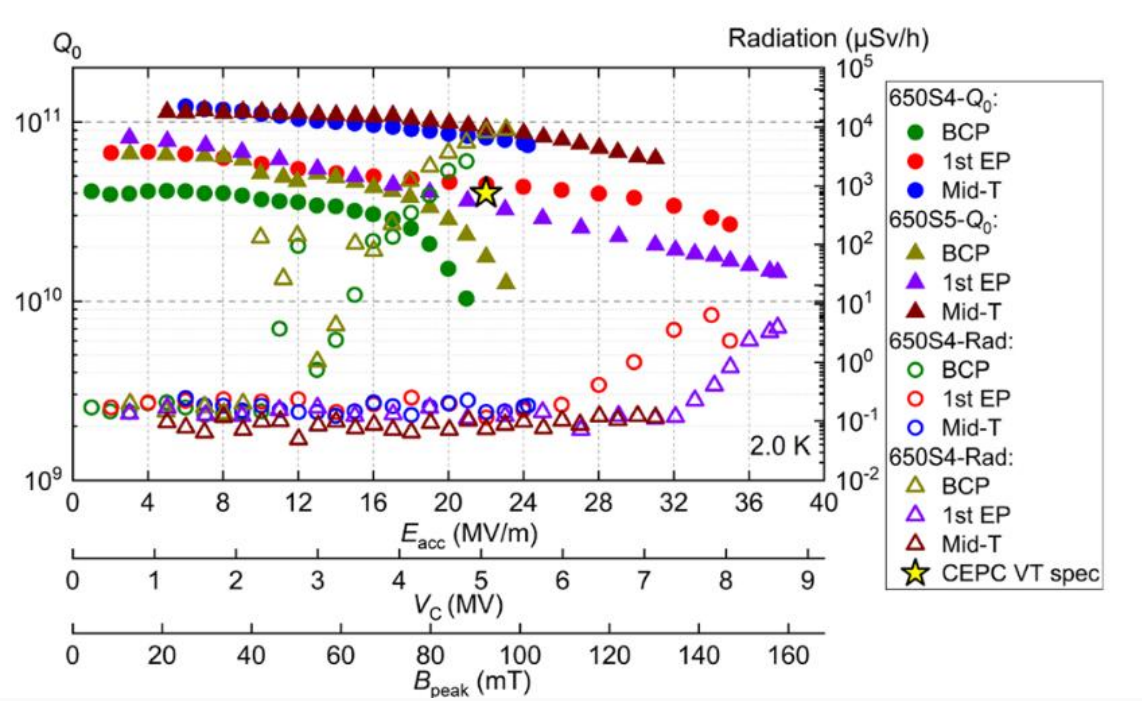
Decision point

Freeze the sequence on the 2-cell prototype results — before the series order is placed, not after.

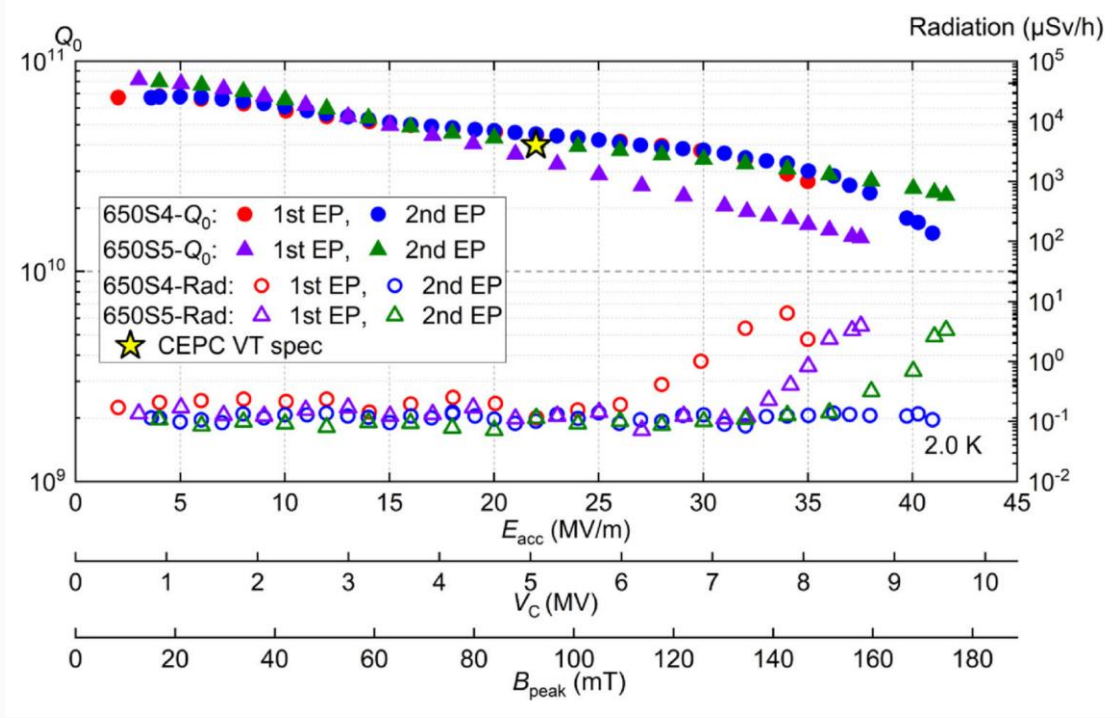
02 650 MHz: what the vertical tests measured

The 650 MHz evidence available today comes from two single-cell cavities published by IHEP. The figures below are reproduced directly from those papers; both are plotted at 2.0 K and both mark the CEPC vertical-test specification.

BCP+EP+Mid-T baseline



EP +the cold second EP



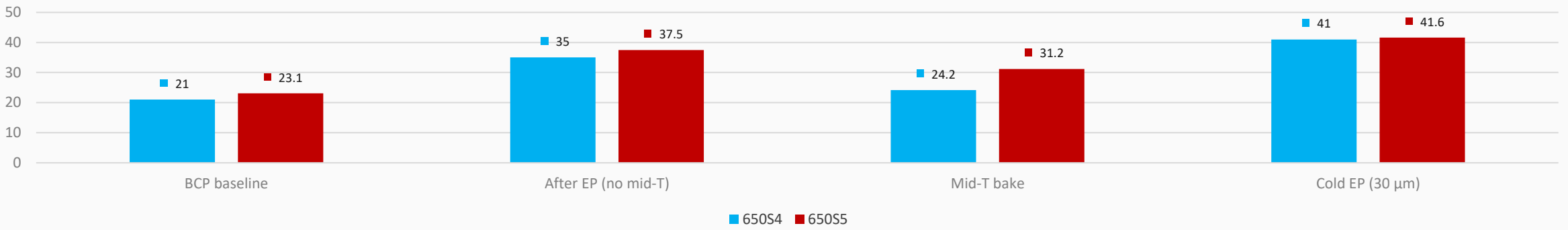
Sha, P., Pan, W.-M., Jin, S., et al. (2022) Nucl. Sci. Tech. 33, 125, Fig. 9.

Reading the two figures: EP is what unlocks the gradient at 650 MHz — BCP alone stops at the specification line. The cold second EP then does the opposite trade: it recovers the quench field to 41 MV/m but gives back the high-field Q0 that the mid-T bake had produced.

02 One target, two numbers: Q0 and E_acc must hold together

Quench field by surface route — 650 MHz single-cell

quench E_acc in MV/m · B_c1 = 170 mT ≈ 40.5 MV/m · acceptance 30 MV/m



The trade, stated once

Cold EP restores the gradient to 41 MV/m, but removes the mid-T layer, so Q0 falls back to ≈ 4.5×10^{10}. Mid-T gives Q0 > 8×10^{10} but drops the quench to 24.2 / 31.2. Neither step alone satisfies**both** acceptance numbers at once (Sha et al. 2022).

What must be true at the end

A cavity is accepted only when **Q0 ≥ 3.6×10^{10} @ 25 MV/m and E_acc ≥ 30 MV/m hold simultaneously**. That single coupled requirement is the whole decision — not a higher Q0, not a higher gradient, but both on the same cavity.

Decision work package

1 · Reproduce the mid-T Q0 (≥ 8×10^{10} @ 22 MV/m) on the 2-cell.

2 · Test a lighter post-mid-T step (short cold EP / low-T bake): Q0 loss < 20 %, quench ≥ 30 MV/m.

3 · Recover the mid-T quench on the BCP + light EP base (650S4: 24.2 MV/m) to ≥ 30 MV/m.

So what? Acceptance is one coupled test: **Q0 ≥ 3.6×10^{10} @ 25 MV/m and E_acc ≥ 30 MV/m at the same time**. BCP + light EP already clears both without mid-T; mid-T lifts Q0 but breaks the gradient. The open task is the lightest post-mid-T step that keeps Q0 high while recovering quench ≥ 30 MV/m.

03

Scale-up to mass production

Benchmarks from comparable cavity programmes, the yield and failure modes to expect, the cost and cycle-time drivers, and the process-capability indices that have to be put in place.

Having settled how the cavities are prepared (Chapter 2), this chapter asks whether that route can be repeated 288 times.

industrial benchmarks **yield and failure modes** **cost, cycle time, Cpk**

03 No programme reached 100 % first pass

Two programmes publish the number that decides a series order — the share of cavities that pass the vertical test first time. Both are far below 100 %; the others publish performance only.

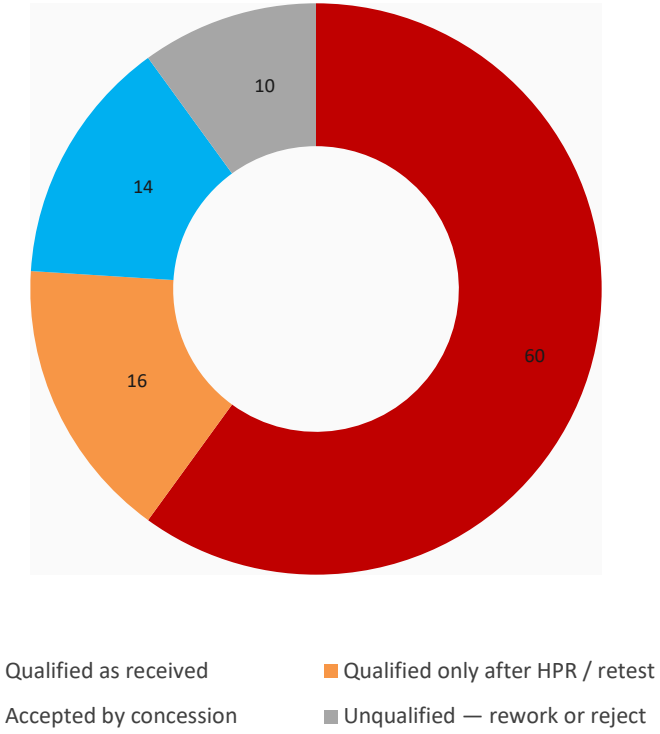
Programme	Production scale	Yield / rework	What CEPC borrows
European XFEL	832 × 1.3 GHz 9-cell · 100 modules	16 % needed rework after the vertical test (Reschke 2017)	Budget rework slots; do not plan on 100 % first pass
SHINE	252 dressed cavities · 5 vendors	60 % as received → 76 % after rework (Chen et al., SRF2025)	Plan on 60 %, qualify each vendor line
CEPC (this study)	**288 cavities • 44 modules • 26 months**	**Target: 60 → 76 % first pass, SPC on every step**	**— (our plan, not a benchmark)**

LCLS-II and LCLS-II-HE demonstrate performance rather than yield: Q0 ≈ 2.8×10^{10} @ 16 MV/m in CW (Gonnella et al. 2018); 24.3 MV/m usable with 2.9×10^{10} @ 20.8 MV/m (Maniscalco 2023).
PIP-II supplies the 650 MHz EP window and mid-T qualification (Chouhan et al. 2023).

So what? No programme ran at 100 % first pass. Budget 16–40 % rework — the range these two bracket — and buy the yield back with process control on the surface steps, not with final inspection.

03 Yield and failure modes at scale

Outcome of 252 dressed 1.3 GHz 9-cell cavities — the SHINE example



SHINE production data, 252 dressed cavities from five industrial vendors*. The same pattern appears at European XFEL, where 16 % of 832 cavities required rework after the vertical test (Reschke et al. 2017).

The number to plan with

76% are qualified in the end — but only 60 % as received; 16 % clear only after HPR or a retest.

Dominant failure modes reported

Field emission **Low Q0**

Field emission and low Q0 account for nearly all of them: of the 24 still unqualified, 20 are too low in Eacc or Q0 and 4 show field emission. The failures are surface or assembly-driven, not design-driven (Reschke et al. 2017).

Field emission in particular originates in particles left by chemistry, rinsing or clean-room handling — the steps that multiply when several vendors each run their own line.

So what? Yield is lost where the process touches the surface. That is a process-control problem — SPC on the chemistry, rinsing and assembly steps — rather than something a final inspection can recover.

* Chen, J., Cao, S., Gong, L., et al. (2025). Status of SRF activities for the SHINE project. SRF2025, MOB04 (JACoW). · Reschke, D., et al. (2017). Phys. Rev. Accel. Beams 20, 042004.

03 Process control, not a formal Cpk

Mass production is usually governed by a capability index — Cpk ≥ 1.33 — but with only 288 cavities (and far fewer before series), a formal Cpk cannot be estimated reliably. The practical substitute is SPC control charts on each unit operation plus 100 % vertical-test inspection.

Unit operation	Key output variable	Control method	Capability today	Dominant risk
Bulk EP / BCP	Removal (µm), surface roughness	Recipe + in-situ I–V monitoring	Medium — temperature and flow dependent	Uneven removal, hydrogen uptake
High-temperature anneal	Hydrogen degassing, RRR	Furnace recipe (T, t, vacuum)	High — well-controlled variable	Furnace contamination
Mid-T bake	Q0, anti-Q-slope	T, time, vacuum + RGA	High — ± 50 °C window still gives high Q0	Furnace cleanliness, air-exposure time
HPR + clean assembly	Particle count, FE onset field	Clean-room class, rinse-water quality	Medium — particle-driven	Field emission
Vertical test (screening)	Q0, E_acc, quench field, FE	100 % inspection at 2.0 K	High — but it is inspection, not control	Consumes cryostat slots; ~10 % measurement uncertainty
Cryomodule assembly	Usable gradient, detuning, dose	Coupler thermal contact, alignment	Medium — new for the 650 MHz module	HOM / input-coupler overheating

Why the arithmetic still holds. Five surface steps at 95 % per step give RTY = $0.95^5 \approx 77$ % — the 76 % SHINE finally reaches; as received it is only 60 % (≈ 90 % per step). Yield is earned step by step, not inspected in at the end — the number to plan with, even where a formal Cpk is out of reach.

04

Outlook and Summary

Lessons from other industries that already run at this scale, the prioritised work packages for the coming years and the conclusions of the review.

cross-industry lessons **prioritised work packages**

04 Cross-industry lessons for cavity mass production

How other industries hold a yield target

Semiconductor

Yield is managed with Cpk, statistical process control and designed experiments, and improves along a learning curve as volume accumulates. The rule is that you control the process, not the product.

Automotive

The production process is frozen and approved (APQP / PPAP) before series build, error-proofing removes the chance of a wrong step, and every supplier line is qualified separately with traceability.

Aerospace

Welding, heat treatment and surface finishing are treated as special processes: certified, first-article inspected and periodically re-validated, with formal non-conformance review when a part misses its limits.

Pharmaceutical / medical device

Equipment and cleaning routines are validated (IQ / OQ / PQ) and any change to a validated step goes through formal change control before it is used on product.

What transfers to 288 cavities

1 • Control the process, not the product

SPC on EP removal, rinse-water quality and assembly cleanliness gives an early signal; the 2 K vertical test only tells you what already happened.

2 • Freeze and validate the recipe

Freeze the mid-T recipe (temperature, hold, vacuum, air exposure) and put any change under formal control, so that data from different cavities stay comparable.

3 • Qualify every vendor line

SHINE used five vendors and still had a 24 % non-conforming rate. Each furnace, EP bath and clean room needs its own capability demonstration before it touches production cavities.

The common thread. Mature industries do not reach 99 % yield by inspecting more; they reach it by making each step incapable of producing a defect, then proving the capability with data.

04 R&D outlook and summary

A prioritised programme that moves the 650 MHz route from "demonstrated on one cell" to "capable in series", and that keeps the 1.3 GHz baseline where it is.

0 – 1 year | **1 – 2 years** | **3 – 5 years**

0–1 YEAR

Measure

Freeze the mid-T recipe — 300 °C / 3 h, ≥ 2 days air exposure, one bulk EP — and place it under formal change control.

Qualify it on the 650 MHz 2-cell: reproduce the mid-T Q0 on the BCP + light EP chain, and run the bulk EP + mid-T variant (no data yet).

Build Cpk baselines and SPC charts for EP removal, rinse-water quality and assembly cleanliness, and run measurement-system analysis on the vertical-test stand.

1–2 YEARS

Close the Q0–gradient gap

Find the lightest post-mid-T step — a short cold EP or a controlled low-temperature bake — that restores E_{acc} ≥ 30 MV/m while keeping the Q0 loss under 20 %.

Size the furnaces to the 26-month batch plan.

Deliver the 650 MHz cryomodule horizontal test (6 × 2-cell, 70 MV) and use it to fix the module-level yield model.

3–5 YEARS

Next-generation surface treatments

Evaluate nitrogen infusion — 35 MV/m demonstrated at 1.3 GHz — as a further Q0 step for the collider cavities if the mid-T route ever needs a higher ceiling.

Add in-line metrology and a predictive yield model so the line shifts from inspection to prevention.

Automate optical surface inspection and particle counting at every hand-off between vendors.

Targets: both acceptance numbers met in one 650 MHz cavity — $Q_0 \geq 3.6\times10^{10}$ at 25 MV/m and $E_{acc} \geq 30$ MV/m — and per-step FPY ≥ 95 % (RTY ≈ 77 %) against ≈ 90 % at SHINE.

Thank you