H2ID Heatmap Laboratory

Interactive Waveform and Harmonic-Termination Exploration for Power Amplifiers

The H2ID Heatmap Laboratory, based on second-harmonic input distortion, transforms RF power-amplifier design from the search for individual optimum operating points into a visual and interactive exploration of high-performance operating regions in a sampled H2ID design space. The Heatmap Laboratory allows the designer to discover, understand and exploit families of favourable operating regions.

Colour-coded heatmaps highlight regions of high efficiency, favourable power factor, high output power, acceptable voltage stress, desired conduction angle, and reduced knee-related degradation. Device constraints can be adjusted interactively to explore the resulting design trade-offs.

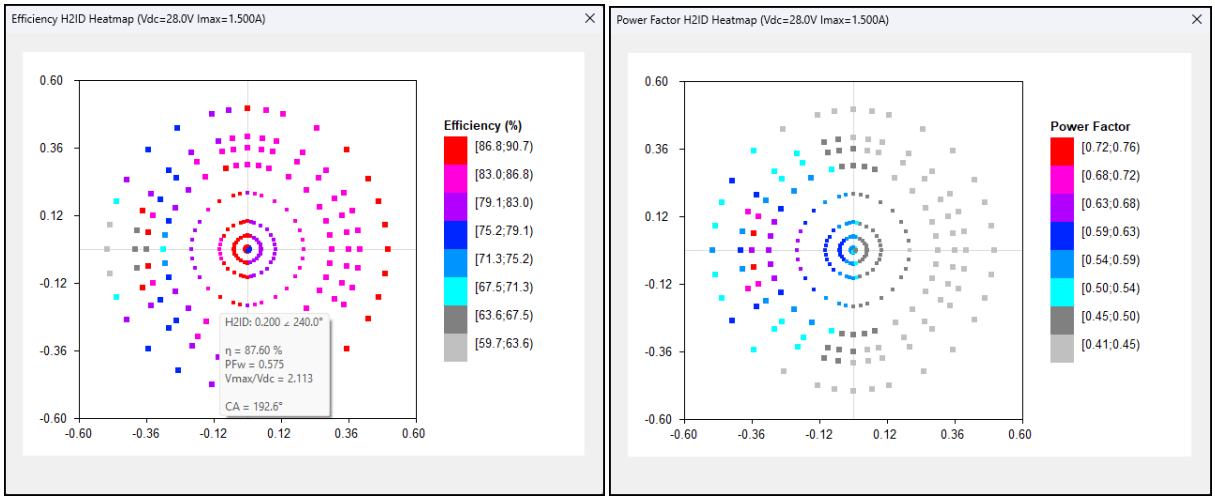

Figure 1. Efficiency and power-factor heatmaps. Moving the cursor over an *H2ID* operating point displays a tooltip. In this example, the transistor knee is ignored.

The H2ID Heatmap Laboratory enables users to:

- Visualise the sampled H2ID design space.
- Apply realistic transistor operating constraints.
- Explore, inspect and compare H2ID operating regions offering a favourable compromise between efficiency, output power, power factor, voltage stress, and current utilisation while avoiding operation beyond the transistor knee boundary.
- Display and compare dynamic load lines, harmonic impedances and the performance at different operating points.
- Show the range of peak currents (I_{max}) over which the performance targets are met at any of the sampled operating points.
- Display the harmonic terminations associated with an operating point on a Smith chart, including the terminations at the selected peak current (I_{max}) and along the valid I_{max} range.
- Create sensitivity heatmaps for any selected operating point. The heatmaps show how perturbations of the fundamental and most sensitive harmonic terminations affect performance and the acceptable range of the least sensitive harmonic termination. Continuous-mode-like behaviour is revealed by these heatmaps. The angular span of the least sensitive harmonic termination over which the performance will be acceptable is calculated at each grid point and can be displayed.
- Display the reflection coefficients associated with a user-selected number of highest-Merit bins on a Smith chart. The number of solutions in each bin is also displayed.
- Perform one-dimensional searches on the fundamental-frequency or the harmonic-frequency perturbations to maximise the performance and establish the range of perturbations over which the specified performance thresholds are satisfied.
- Perform real-time "what-if" analysis using interactive sliders.

The laboratory maps each H2ID vector to its associated normalised intrinsic output-current waveform. For each operating point, a complementary normalised voltage waveform is synthesised to maximise waveform efficiency. The voltage waveform contains only the fundamental, second, and third harmonics, and negative load resistance is not permitted. Once the waveforms are defined, the normalised intrinsic harmonic load impedances are known.

Output power depends on the selected complementary waveform pair, its power factor, the targeted peak current, and the applied *dc* voltage. The transistor knee introduces a practical trade-off between output power and efficiency. At high power levels, knee interaction can substantially reduce efficiency. Reducing the targeted peak current lowers output power while allowing efficiency to approach the waveform efficiency.

For a specific transistor, the normalised current waveform is scaled to the selected peak current, and the voltage waveform is scaled to touch the knee boundary at the specified *dc* voltage. These scale factors determine the intrinsic harmonic load impedances. If a suitabe transistor model or output-parasitic network is available, the intrinsic impedances can also be mapped to the external reference plane. In summary:

H2ID vector → Normalised intrinsic output-current waveform → Complementary voltage waveform → Current scaled to the selected peak → Voltage scaled to touch the knee boundary at the specified *dc* voltage → Intrinsic harmonic load impedances → External harmonic load impedances (when mapping is available).

The intrinsic harmonic impedances associated with an H2ID operating point can be perturbed to evaluate sensitivity and investigate whether performance can be improved by introducing fundamental-frequency reactance. Such improvements may require corresponding adjustments to the harmonic terminations.

For perturbed intrinsic impedances, the generalized analysis determines the current scaling required to reach the knee boundary. The normalized current waveform remains determined by the selected H2ID operating point, but the current and voltage scaling factors are no longer independent.

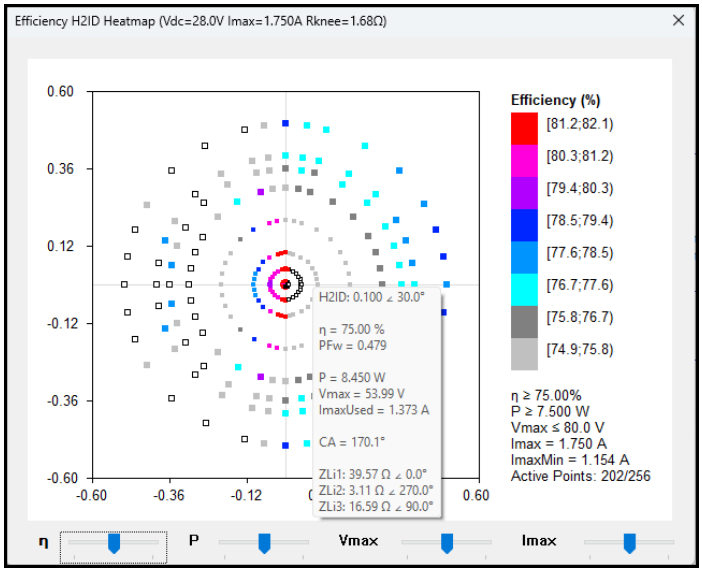

Figure 2. Effect of the transistor knee on efficiency. Constraint sliders allow the acceptable efficiency, power, voltage, and current limits to be adjusted interactively.

Up to six H2ID operating points can be inspected simultaneously. The inspectors show efficiency, power factor, output power, conduction angle, harmonic load impedances, voltage stress, current utilisation, knee factor, and dynamic load-line behaviour. Selected inspector windows remain open as device

parameters or constraints are changed, enabling immediate before-and-after comparisons. An option in the heatmap and device settings clears the inspector selections and window positions.

The knee boundary can be represented by a straight line (constant knee resistance) or by a piecewise-linear curve defined by up to eight points. Linear interpolation between adjacent points permits a close fit to the transistor knee characteristic. Operation beyond the knee boundary, including clipping and compression, is not modelled: the laboratory determines the maximum unclipped operating condition. For Class-B-like and Class-F-like operating points, saturated power is typically a few decibels higher than the calculated maximum unclipped power.

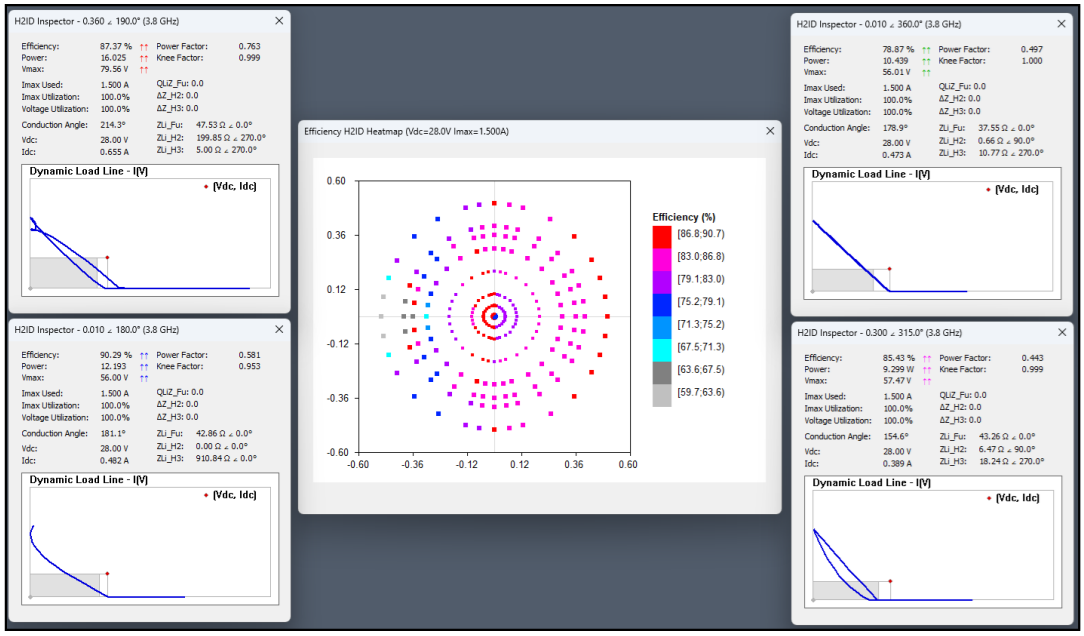

Figure 3. Inspectors for several H2ID operating points, with the transistor knee ignored. Red dots mark the dc operating points; shaded rectangles represent output power relative to dc power.

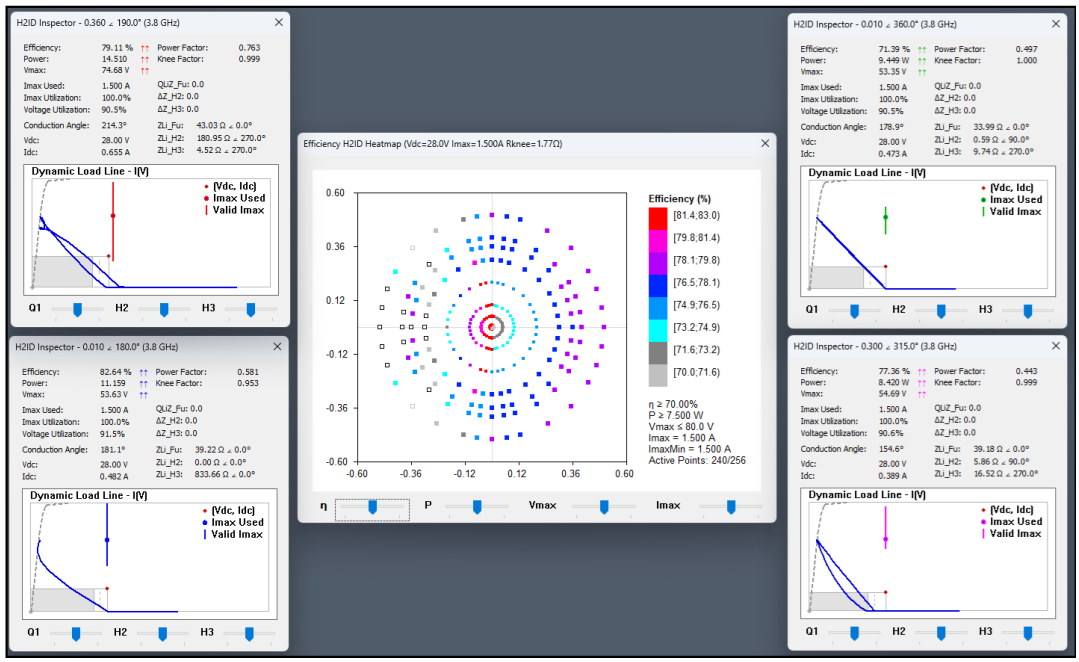

Figure 4. The same operating points as in Figure 3, now including knee degradation. Dashed grey lines mark the knee boundary. The valid maximum-current (I_{max}) ranges are shown in the inspector colours; they turn grey when the specified efficiency and power targets are not met. Coloured up arrows become darker down arrows when performance falls outside the target range.

The inspectors' dynamic load lines provide a direct visual check of the waveform synthesis. Each load line stays outside the excluded knee region and touches the knee boundary at the point implied by the waveform solution. Designers can therefore assess waveform behaviour and transistor constraints immediately.

The Heatmap Laboratory uses an equivalent cascade of up to three shunt capacitors and three series inductors to map intrinsic load impedances to the external reference plane. ADW also provides a more general, linear power-parameter mapping method that permits internal feedback and resistive losses; it is not restricted to a lossless cascade network.

Rather than asking only which load impedance satisfies a given design condition, the H2ID Heatmap Laboratory shows which regions of the sampled design space meet the efficiency, power, voltage, and current constraints. The designer can then determine the harmonic terminations needed to realise a selected operating point.

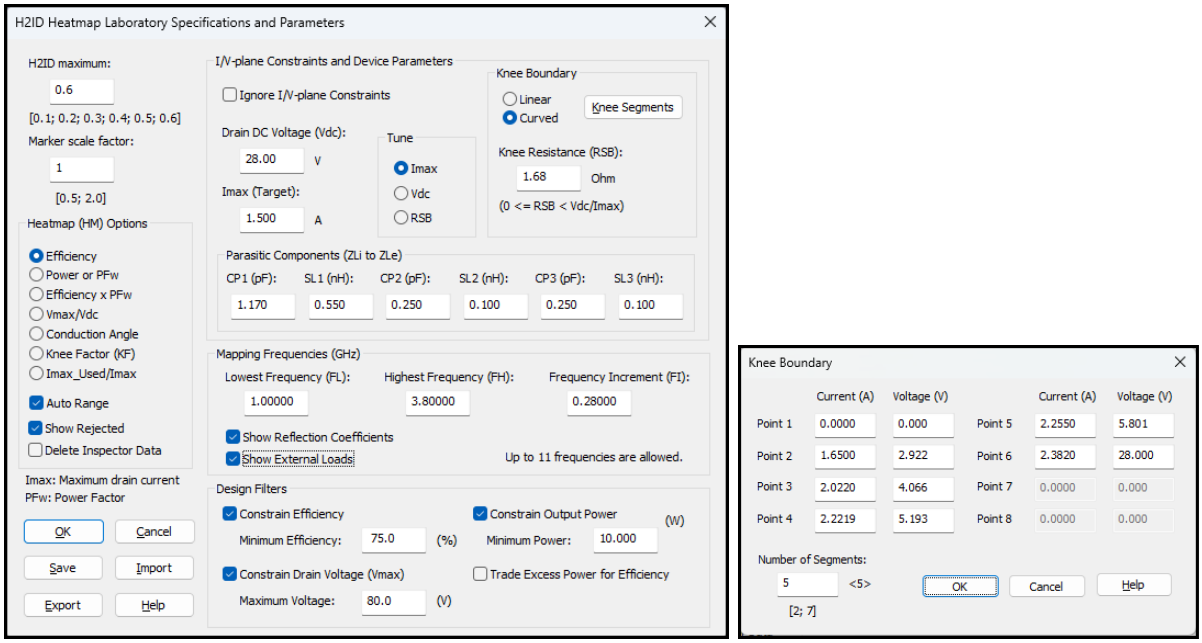

Figure 5. Heatmap and device settings, design filters, and display options.

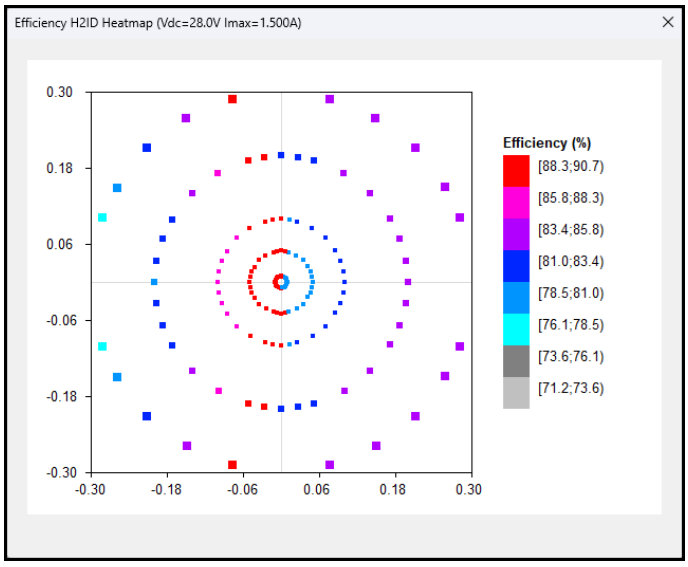

Figure 6. The *H2ID* range has been reduced from 0.6 to 0.3. Note the Class-F-like and Class-B-like high-efficiency regions at low distortion levels.

Figure 5 shows the laboratory controls, including adjustments for marker size and H2ID range. With Show Rejected selected, operating points that fail the targets appear as hollow markers; otherwise, those markers are hidden.

When the knee boundary is enabled, the Trade Excess Power option reduces the targeted peak current to improve efficiency where excess output power is available.
The Save and Import commands store and restore device specifications and design filters.

Each inspector can be assigned a different frequency. Clicking the empty area immediately below an inspector heading opens the control shown in Figure 7. The H2ID operating point and frequency can be changed, and the peak current can be frozen for that inspector. Subsequent adjustments to the main I_{max} control then leave the frozen inspector current unchanged.

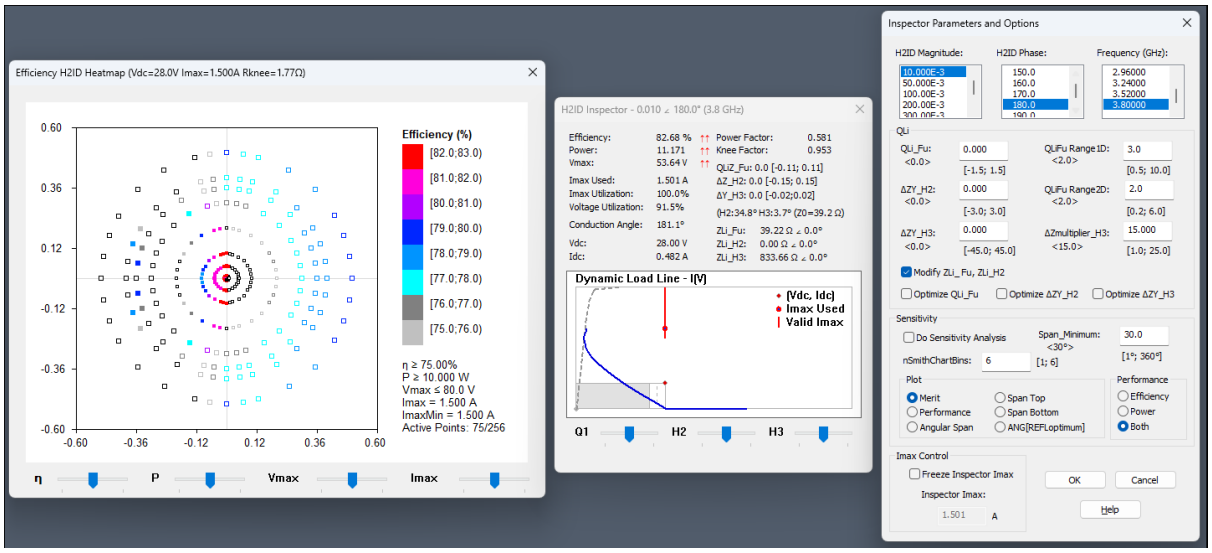

Figure 7. Inspector H2ID, frequency, and I_{max} controls. The operating point and frequency can be changed, and the inspector's maximum current can be frozen.

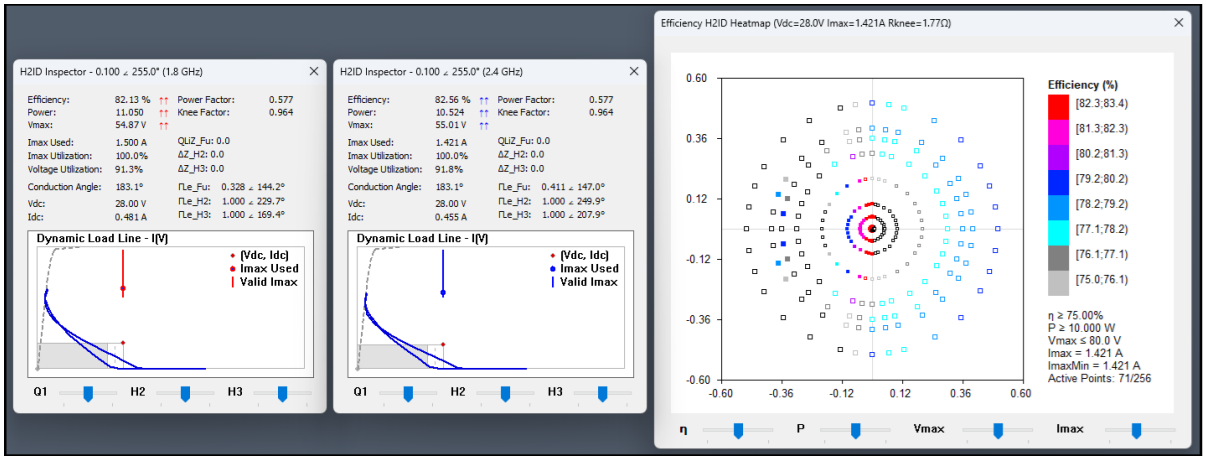

Figure 8. Different frequencies and independently selected operating conditions can be assigned to individual inspectors.

When at least one inspector is open, double-clicking the empty area below the heatmap heading opens a Smith chart (Figure 9). It displays the harmonic terminations of the open inspectors, including those along each valid Imax range. Traces use the colours assigned to the inspectors. Individual inspectors, or all second- or third-harmonic traces, can be hidden.

Assigning different frequencies and operating conditions to the inspectors reveals how the required fundamental-, second-, and third-harmonic reflection coefficients vary across a band. Candidate

operating-point trajectories (mode migration) can be explored before their harmonic terminations are used as broadband matching-network targets.

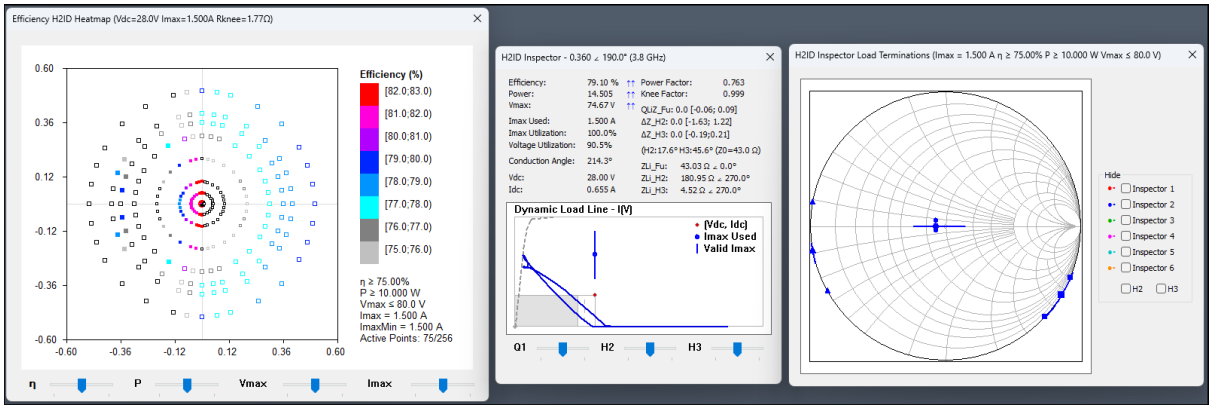

Figure 9. Double-clicking the empty area below the heatmap heading opens a Smith chart showing the inspectors' harmonic terminations.

Clockwise rotation of the second- and/or third-harmonic reflection coefficients may ease matching-network synthesis. The second harmonic is especially important for Class-B-like and Class-F-like operating points, including continuous-mode-like solutions, whereas the third harmonic is especially important for inverse Class-F-like operating points. Anticlockwise rotation of the fundamental-frequency reflection coefficient can be easier to accommodate, for example with a resonance loop. The laboratory calculates and displays the angular spans of the harmonic reflection coefficients. Anti-clockwise rotation is indicated as a negative span.

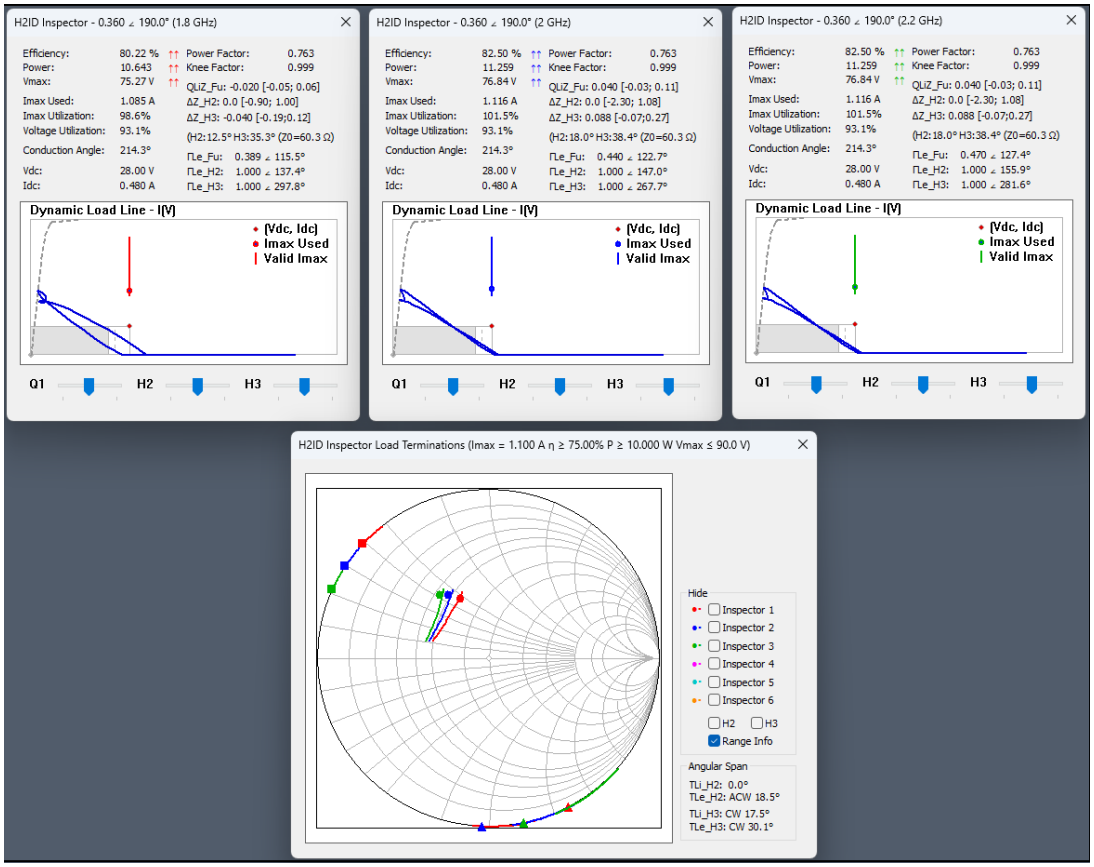

Figure 10. Harmonic-termination trajectories across the targeted passband. Inspectors were assigned different frequencies at the same H2ID operating point (no mode migration). The resulting trajectories illustrate how modifying the Q_{Li_Fu} values of individual inspectors can shape a harmonic trajectory to rotate clockwise. Automatic compensation was applied first, then disabled for manual fine-tuning of the third-harmonic trajectory.

The maximum current selected for each inspector strongly influences output power, efficiency, and the fundamental-frequency termination. The second- and third-harmonic terminations depend on the selected complementary waveforms and peak currents.

Inspector Tuning and Harmonic Compensation

For the default complementary waveforms, the intrinsic fundamental-frequency load terminations are purely resistive. The intrinsic fundamental-frequency Q-factor (Q_{Li_Fu}) can be changed from zero using the inspector control or fundamental-frequency slider (Q_1). Introducing fundamental reactance without compensating harmonic tuning generally degrades performance.

For Class-B-like or Class-F-like operating points, this loss of performance can be restored fully or partially by adjusting the intrinsic second-harmonic load impedance. Adjustment is manual using the second-harmonic slider (H_2), or automatic using the Optimize ΔZY_H_2 option in the inspector control. Automatic compensation disables the H_2 slider. Continuous-mode-like operation can be obtained at the optimum point when the magnitude of Q_{Li_Fu} is sufficiently small; the knee restricts the range over which perfect compensation is possible.

Exact continuous-mode inverse-Class-F-like operation is not modelled by the current implementation of the laboratory. The H2ID operating point fixes the shape of the intrinsic output current; obtaining the required current shaping would involve introducing third-harmonic content into the intrinsic input voltage. For small fundamental-frequency Q-factors, tuning the intrinsic third-harmonic load impedance may nevertheless recover some or all the lost performance (see Figure 10).

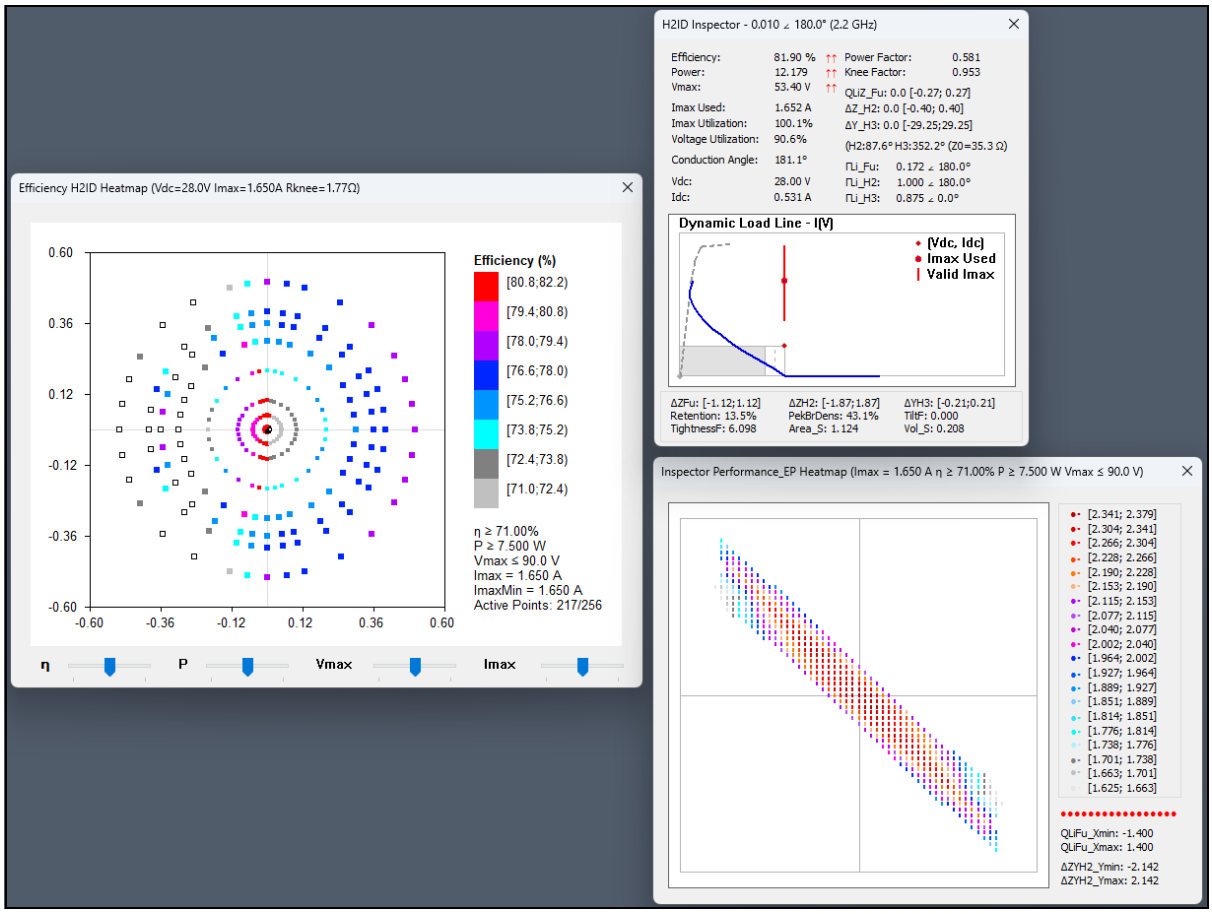

Figure 11. An example of a Class-F-like performance heatmap. In the red area the performance is similar or close to the H2ID operating point performance without any perturbations (82%, 12W; continuous-mode behaviour).

Sensitivity analysis at a selected H2ID operating point provides heatmaps of

- Performance
- Merit
- Angular span of the insensitive harmonic terminations
- Span bottom
- Span top
- Optimum angle in the span

The two-dimensional sensitivity grid is defined by the fundamental-frequency termination (X-axis) and the most sensitive harmonic termination (Y-axis). At each grid point, the laboratory determines the acceptable reactance or susceptance range of the least sensitive harmonic termination (Z-axis). The angular span of the associated reflection coefficients is calculated and can be displayed.

The Performance measure considers only operating points that satisfy the specified efficiency and output-power thresholds. It can be based on efficiency, output power, or both. For each acceptable grid point, the excess efficiency and output power above their respective minimum thresholds are normalised against the corresponding margins defined by the knee-limited maximum efficiency (η_{OP}) and power (P_{OP}) of the selected H2ID operating point at the maximum current level targeted:

$$\text{Performance} = 1.0 + \sqrt{\{[(\eta - \eta_{threshold})/(\eta_{OP} - \eta_{threshold})]^2 + [(P - P_{threshold})/(P_{OP} - P_{threshold})]^2\}}$$

The Performance measure equals 1.0 when the efficiency and output power are at their minimum acceptable levels. When both quantities are considered, its maximum is $(1+\sqrt{2})$, provided neither normalised excess exceeds unity. However, perturbations of the fundamental-frequency and harmonic terminations can sometimes improve performance beyond the original knee-limited reference values, producing a Performance measure greater than $(1+\sqrt{2})$.

The merit of a grid point is taken to be the performance scaled by a factor derived from the angular span of acceptable perturbations of the insensitive harmonic termination. This factor is set to 0.5 for a point match, increasing to 0.95 for spans equal to the target set, and 1.0 for 360° spans. Linear interpolation is used for intermediate values.

An example of a performance heatmap is provided in Figure 11 for a Class-F-like H2ID operating point. Continuous-mode-like behaviour is revealed by the heatmap. The associated merit heatmap is shown in Figure 12. The span targeted in this example was 15°. This user-adjustable target controls the trade-off between performance and harmonic termination tolerance. Depending on the performance thresholds, much larger spans can be targeted at some H2ID operating points. If the span is 360°, the performance will be acceptable for any angular perturbation in the least sensitive termination on the investigated termination trajectory.

The diagonal high-performance and high-Merit regions in Figures 11 and 12 demonstrate that fundamental and sensitive-harmonic terminations are related. The size of the XY-region is a measure of the available freedom in selecting acceptable load terminations for the fundamental-frequency and the sensitive harmonic. Acceptable ranges of the insensitive harmonic provide additional freedom for practical matching.

The acceptable perturbations define a volume in perturbation space (ΔQ_{Li}) in which the performance with meet the design thresholds set. The acceptable fundamental-frequency and sensitive harmonic perturbations define the XY limits, while the lower and higher edges of the angular span for the least sensitive harmonic define the Z-axis limits. The Span Bottom and Span Top heatmaps reveal the angular positions of the boundaries of this acceptable region.

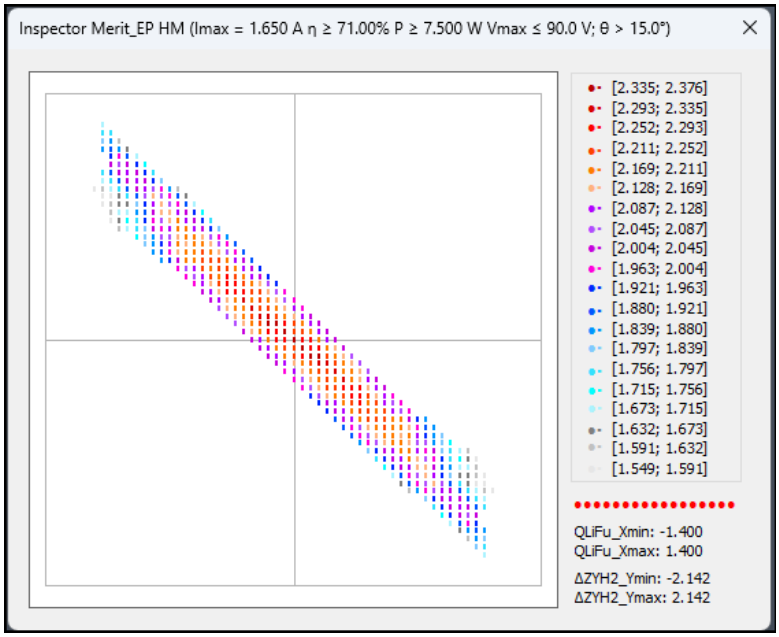

Figure 12. The merit heatmap associated with the performance heatmap shown in Figure 11.

An example of the information displayed by a heatmap tooltip is provided in Figure 13. The heatmap shows the angular span of the insensitive harmonic over which the performance will be acceptable at each grid point. Note that the spans are close to 360° around the centre of the high-performance region.

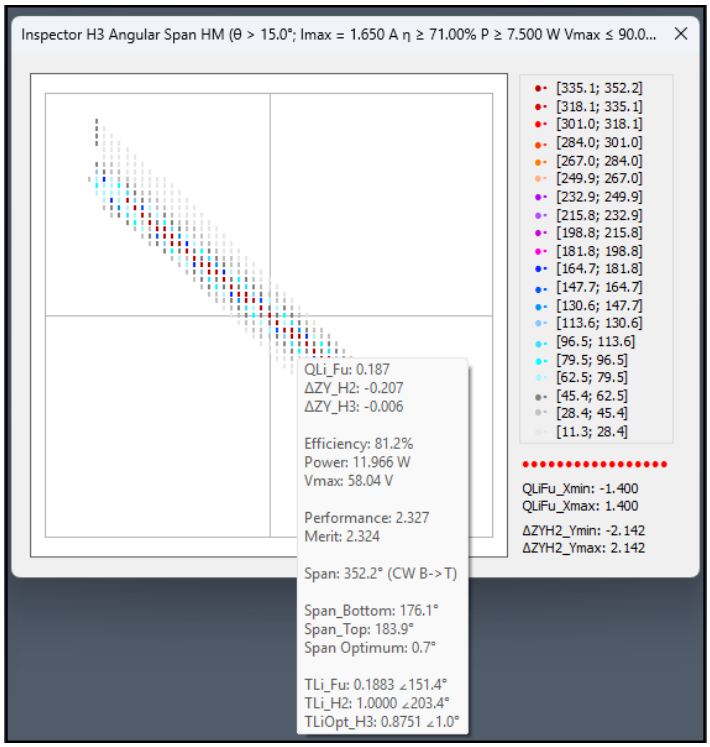

Figure 13. The tooltip information displayed for the inspector heatmaps. The heatmap is for the angular span of the reflection coefficients required for the insensitive harmonic.

The intrinsic or external reflection coefficients associated with a user-selected number of the highest-Merit bins can be displayed on a Smith chart. See Figure 14 for an example. The number of grid points in each bin is also displayed. Note that the tracking required between the fundamental-frequency and the harmonic terminations is not evident from the terminations. Furthermore, only the optimum point

for the least sensitive harmonic is displayed – showing the span for each grid point will make the plot unintelligible.

The intrinsic fundamental-frequency resistance is constant in the Smith chart shown. The heatmaps in this example were created for the centre point in the I_{max} span. Heatmaps can be created for more points in the range – the resistance will then change accordingly. At the boundaries of the valid I_{max} range, the acceptable harmonic perturbation intervals may reduce to individual points.

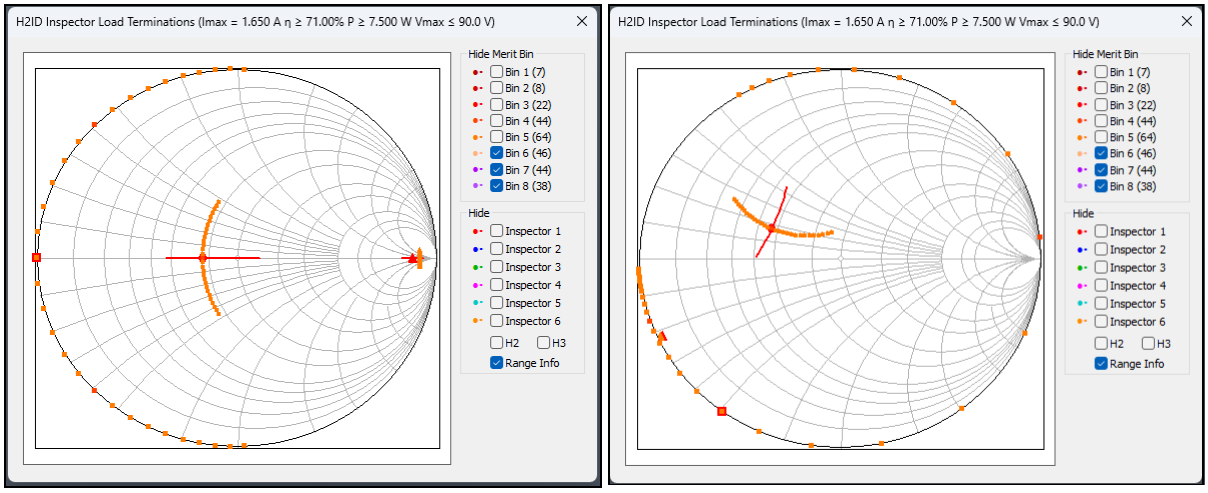

Figure 14. Examples of Smith charts created for the intrinsic and external terminations associated with the top five bins of the Merit heatmap shown in Figure 12. The intrinsic terminations are transformed by the output-parasitic network to the external terminations shown.

These results suggest that matching-network synthesis can benefit from targeting the acceptable perturbation volume rather than independently selected reflection-coefficient targets. This approach preserves the relationship between the fundamental-frequency and sensitive-harmonic terminations while exploiting the available freedom in the insensitive harmonic.

The benefits of targeting intrinsic rather than external terminations have already been demonstrated in the Ampsa ADW CIL Wizard. It is also important to recognise that resonant behaviour at the intrinsic reference plane can differ significantly from that at the external reference plane.

The H2ID Heatmap Laboratory turns the search for a single optimum into an interactive exploration of feasible RF power-amplifier operating conditions. Designers can inspect and compare candidate points, examine frequency-dependent behaviour, and identify harmonic termination targets for implementation. Fundamental-frequency reactance, harmonic compensation, mode migration, and changes in peak current provide additional design freedom.

The Heatmap Laboratory is an option in Version 25 of the Ampsa Amplifier Design Wizard. Version 25 of ADW is scheduled for release on 1 February 2027. Contact Ampsa for pricing and advance orders:

Ampsa (Pty) Ltd www.ampsa.com mail@ampsa.com

Technical background: The second-harmonic input-distortion (H2ID) concepts behind this approach are described in “Second-Harmonic Input Distortion in Power Amplifier Design”, IEEE Microwave Magazine (Early Access), 15 September 2026, doi:10.1109/MMM.2026.3727968.