High Frequency ≠ High Power Density: The Frequency Knee of 3 kW / 800 V LLC Transformers and a 400 kHz Design Example

Why pushing toward 1 MHz can lose power density — a loss-volume model, a knee criterion, and a reproducible worked design

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01 Core Conclusion

In one sentence: for LLC resonant transformers above 3 kW on an 800 V bus, switching frequency contributes to power density only up to a pronounced "knee" — the engineering sweet spot sits at 400–500 kHz. Pushing past that knee toward 1 MHz drives core loss up exponentially and forces costly specialty materials and fine winding processes, while the volume benefit decays to sub-linear. The net result is a negative engineering ROI.

> **Key criterion:** "Higher frequency = higher density" holds only before the knee. With the thermal boundary and material system fixed, going from 100 kHz to 400 kHz cuts transformer volume by ~55%; going from 400 kHz to 1 MHz (a further 2.5× in frequency) cuts only ~27% more, while total loss rises and the added cooling structure eats back the volume saved.
>
> **Engineering takeaway:** invest in 400–500 kHz planar / litz-wire transformers rather than a 1 MHz spec on paper — this is the band that today's 800 V energy-storage and server DC-DC production prototypes actually use.

This article first builds a frequency–loss–volume causal model that proves the knee exists, then gives a complete, reproducible 400 kHz, 3 kW, 800 V→48 V half-bridge LLC transformer design as evidence, and finally uses 1 MHz as a counter-example. All quantitative figures are order-of-magnitude estimates based on public Steinmetz material parameters and standard engineering assumptions (not measured data); they illustrate trends and criteria. Any specific project must be confirmed by prototype testing.

02 Background: Why "Just Raise the Frequency" Is Mistaken for a Universal Density Key

In 800 V platform power design (AIDC HVDC, energy-storage PCS, EV fast charging), engineers naturally want higher power density. A widely repeated maxim is "raise the switching frequency → shrink the magnetics → raise power density." The first half is true at low frequencies: primary turns are inversely proportional to flux swing, and flux swing is inversely proportional to frequency, so a higher frequency permits fewer turns and a smaller core window and cross-section.

But this causal chain has an overlooked brake — core loss. Ferrite core loss follows the Steinmetz equation: $Pv = k \cdot f^{\alpha} \cdot B^{\beta}$, where the frequency exponent α for power ferrites is roughly 1.4–1.7 and the flux-density exponent β is roughly 2.3–2.8. So as frequency rises, even if you lower B by reducing turns, core loss can still increase net, because f^{α} grows faster than B^{β} falls. How small a transformer can ultimately be is governed not by "how few turns" but by "whether the resulting loss can be removed within an acceptable temperature rise." That is the real density constraint: the thermal wall, not the turns wall.

Two paths to "smaller volume" with opposite endings

Path A (frequency-for-volume, low band): higher frequency → fewer turns → smaller core, loss stays controllable, density rises net. Path B (frequency-for-volume, high band): frequency keeps rising → core loss climbs as f^{α} and winding AC resistance worsens from skin/proximity effects → to contain loss you must enlarge the core or add cooling → the volume saved is eaten back. The knee is where Path A turns into Path B.

The table below re-optimizes the core size of the same 3 kW / 800 V→48 V LLC transformer at each frequency under a unified thermal boundary ($\Delta T \approx 40$ K), revealing the true trajectory of density and loss versus frequency — this is the primary comparison table for locating the knee.

Frequency	Core material (best for band)	Optimized Bmax	Primary turns	Total loss (order)	Efficiency (order)	Relative volume
100 kHz	PC95 class	≈150 mT	26	≈28 W	99.07%	1.00× (ref.)
200 kHz	PC95 class	≈110 mT	18	≈27 W	99.10%	0.62×
400 kHz	PC95/DMR95	≈75 mT	16	≈28 W	99.07%	**0.45×**
700 kHz	PC200 class (specialty)	≈55 mT	14	≈31 W	98.97%	0.36×
1 MHz	PC200 class (specialty)	≈45 mT	13	≈37 W	98.77%	0.33×

Three readings: (1) Volume-benefit cliff — 100k→400k saves 55%, but 400k→1MHz raises frequency another 2.5× for only ~27% more, a badly imbalanced input/output. (2) Loss backlash — total loss is optimized down to ~28 W across 100k–400k, then jumps to ~37 W at 1 MHz; the extra ~9 W lands on a deliberately shrunken core, raising temperature-rise risk and demanding extra cooling that eats volume back. (3) Material/process cliff — above 700 kHz you must switch to PC200-class specialty material (several times the cost, high MOQ, long lead time) and force fine litz or multilayer-PCB windings, sharply raising yield risk and prototyping cost.

Note: the table gives order-of-magnitude estimates to reveal the trend and knee location, not measured values of any one design. Absolute numbers vary with core geometry, material batch, cooling conditions, and winding process, and require project confirmation.

03 Anatomy of the Knee: Four Engineering Constraints Tightening at Once

3.1 Core loss: the exponential brake of f^α

In the Steinmetz equation the frequency exponent α for power ferrites is typically 1.4–1.7. Raising frequency from 400 kHz to 1 MHz (2.5×) lifts the frequency term of volumetric loss to about 2.5^1.5 ≈ 4.0×. The only way to push that loss back down is to drop Bmax sharply (from 75 mT to 45 mT) — but lowering B locks the room to reduce turns and prevents proportional core shrinkage. That is the root cause of the decaying volume benefit. Switching to PC200-class low-loss specialty ferrite improves α/k, but the price moves to material cost and supply.

3.2 Winding AC loss: skin and proximity effects

Copper skin depth δ is inversely proportional to the square root of frequency: at 100 °C, ≈104 μm at 400 kHz, ≈79 μm at 700 kHz, ≈66 μm at 1 MHz. When conductor thickness or diameter far exceeds δ, current is pushed to the surface and AC resistance Rac rises well above DC resistance Rdc; their ratio Fr climbs steeply. For a 3 kW secondary at high current (≈62.5 A with 800 V in, 48 V out), a thick solid conductor or wide-edge flat wire can reach Fr of 3–5 at 1 MHz, so winding loss is actually worse than at 400 kHz. The high-band remedy is fine-strand litz or multilayer-PCB planar windings — which is precisely what raises process difficulty and cost.

3.3 The thermal wall: the real ceiling on density

The physical ceiling on power density is not "how small the core can be" but "how much heat a unit of surface can dissipate." A transformer's surface dissipation scales roughly with surface area, which scales with the 2/3 power of volume. When higher frequency increases loss while you also shrink volume, heat-flux density (W/cm^2) worsens on both fronts, and temperature rise rapidly approaches the red lines of the material Curie temperature and insulation temperature class. Once the wall is hit, you either add cooling structure (potting, air ducts, thicker copper foil — eating volume) or retreat to a larger core — both cancel the high-frequency volume benefit.

3.4 The material and process cost cliff

At 400 kHz and below, mainstream power ferrites such as PC95 and DMR95 are stably mass-produced domestically at friendly prices and flexible MOQs; windings use conventional magnet wire or coarser litz with mature processes. Beyond roughly 500–700 kHz you must switch to PC200- or ML91S-class high-frequency specialty materials at several times the cost, with long lead times and high MOQs; windings are forced into fine multi-strand litz or multilayer-PCB planar structures, lowering yield and raising both prototyping and production cost.

Frequency Knee Decision Card

- **Default band:** for LLC transformers above 3 kW on an 800 V platform, anchor on 400–500 kHz by default; do not lunge toward 1 MHz without a topology or EMI hard constraint.
- **Signals to lower frequency:** core loss >50% of total, temperature rise approaching material/insulation red lines, or needing PC200-class material to meet spec — any one means you are past the knee; retreat in frequency to recover loss and cost margin.
- **Signals to go litz/planar:** winding Fr >2, or secondary current >40 A with a thick solid / wide-edge flat conductor — switch to fine-strand litz or multilayer-PCB planar windings.
- **In a line:** frequency is not "the higher the better" but "as high as needed"; invest the saved margin in cooling and winding process for a more robust density gain.

04 Core Material Comparison: The Wrong Material Brings the Knee Forward

The core material sets where the knee appears on the frequency axis. The table compares power-ferrite grades common in 800 V LLC transformers across frequency suitability, loss, temperature, and cost. Values are public reference figures and require project confirmation.

Material grade (class)	Recommended band	Rel. core loss (same f)	Bs (ref.)	Curie temp (ref.)	Supply / cost
PC95 / DMR95 (power ferrite)	≤400 kHz	baseline	≈530 mT	≈215 °C	domestic mass-prod · low cost · friendly MOQ
PC90 / 3C95 (mid-freq power)	≤300 kHz	slightly higher	≈530 mT	≈220 °C	mature · medium cost
PC200 / ML91S (HF specialty)	400 kHz–1 MHz+	markedly lower	≈390 mT	≈250 °C	several× cost · high MOQ · long lead
Nanocrystalline/amorphous (niche)	wide / special	low (Bs/geom. limited)	by grade	high	high cost · geometry-limited

Interpretation: at 400 kHz, PC95/DMR95 is still within its economic comfort zone — the material-level reason the knee lands at 400–500 kHz. Forcing 700 kHz–1 MHz makes PC95 loss unacceptable, requiring a switch to PC200-class material; the high band beyond the knee essentially compensates for physical loss with material cost. That is why the 1 MHz option hides BOM-cost and supply-chain risk behind its "paper volume."

05 Winding & Insulation: The Three-Way Trade-off of 800 V / High-Frequency / High-Current

800 V means high insulation demand, high frequency means low Rac demand, and high current means low Rdc demand — the three constrain one another. The table compares three winding approaches for this scenario.

Winding approach	HF Rac (Fr)	High-current capacity	800 V insulation fit	Process / cost	Fit for this case
Thick solid round / flat wire	poor (high Fr)	good	needs thick insulation	mature · low	OK ≤200 kHz · degrades at HF
Multi-strand fine litz	**excellent (low Fr)**	good (enough strands)	strong interlayer insul.	med-high · winding skill	**first choice 400 kHz high-current**
Multilayer PCB planar	excellent (controllable)	limited by Cu thick/layers	controllable stack insul.	tooling/PCB cost high	HF high-density mainstream · medium current

Insulation and creepage: an unavoidable 800 V constraint

On an 800 V bus, the insulation withstand voltage, creepage distance, and clearance between primary and secondary and between winding layers must meet the relevant safety class. Common approaches use triple-insulated wire (TIW) or add polyimide/Nomex insulation between layers. At high frequency, common-mode noise and dielectric loss from inter-winding parasitic capacitance also matter. These requirements inherently conflict with "smaller volume" — insulation occupies window area, further squeezing the room to shrink at high frequency, and is another driver of the knee.

06 Complete 400 kHz Design Example: 3 kW · 800 V→48 V Half-Bridge LLC Transformer

Below is the reproducible evidence behind the "knee at 400 kHz" conclusion. Inputs are locked to a typical 800 V platform energy-storage / server DC-DC; every step is shown so engineers can verify it themselves.

6.1 Design inputs

Parameter	Symbol	Value	Note
Topology	—	Half-bridge LLC	resonant conversion
Bus voltage	Vin	760–820 V (nom. 800 V)	800 V platform
Output voltage	Vout	48 V	typical DC-DC output
Output power	Pout	3 kW	secondary current ≈62.5 A
Resonant frequency	fr	400 kHz	knee sweet spot
Gain design point	M	M = 1 @ fr	normalized operating point

6.2 Turns ratio and turns

At resonance the half-bridge LLC voltage gain is 1, so the effective turns ratio $n = V_{in\_nom} / (2 \cdot V_{out}) = 800 / (2 \times 48) = 800/96 \approx 8.3$; take n = 8, i.e. Np:Ns = 16:2.

Primary turns follow from Faraday's law: $N_p = V_{in} \cdot D / (4 \cdot f_r \cdot B_{max} \cdot A_e)$. With duty D ≈ 0.5, Bmax = 75 mT (kept low to suppress core loss at high frequency), and a planar ELP/E38-class core with effective area Ae ≈ 194 mm²: $N_p \approx (800 \times 0.5) / (4 \times 400 \times 10^3 \times 0.075 \times 194 \times 10^{-6}) \approx 16$ turns, consistent with the 16:2 ratio. Secondary Ns = 2 turns.

6.3 Resonant parameters (Lm / Lr / Cr)

The magnetizing inductance Lm and resonant inductance Lr are not set by the transformer alone but locked together with the resonant capacitor Cr, the gain curve, and the frequency-modulation range. Engineers commonly use Lm/Lr ≈ 5–7 to balance gain range and light-load ZVS. Here: $f_r = 1/(2\pi \cdot \sqrt{L_r \cdot C_r})$. First fix Lm ≈ 30–50 μH from ZVS dead-time and magnetizing-current needs, then set Lr from the Lm/Lr ratio, then back-solve Cr from fr = 400 kHz. The exact values must be solved jointly with the actual resonant tank and control strategy and confirmed by prototype; this gives the method chain rather than a single locked number, to avoid divorcing it from the specific resonant design.

6.4 Winding selection (critical)

Secondary current ≈62.5 A, 400 kHz, skin depth ≈104 μm. Conclusion: use multi-strand fine litz on the secondary (single-strand diameter on the order of $\leq 2\delta \approx 0.2$ mm), with strand count set jointly by current capacity and temperature rise; the 16-turn primary carries less current and can use finer litz or a multilayer structure. A thick solid or wide-edge flat conductor is not recommended as the secondary here — its Fr at 400 kHz would noticeably raise winding loss. For extreme density at controlled current, evaluate a multilayer-PCB planar winding.

6.5 Loss and temperature-rise breakdown (order-of-magnitude)

Loss item	Order	Main cause	Suppression
Core loss Pcore	≈15 W	$f^\alpha \cdot B^\beta$ (Steinmetz)	low Bmax (75 mT) · PC95/ DMR95
Winding loss Pcu	≈13 W	Rdc + HF Rac (Fr)	litz lowers Fr · enough Cu area
Total Ploss	≈28 W	—	—
Efficiency (order)	**≈99.07%**	3 kW @ 28 W loss	—
Temp. rise ΔT	**≈40 K (target wall)**	heat-flux limited by surface	potting/thermal interface · limit hotspot

1 MHz counter-example: pushing the same design to 1 MHz requires PC200-class material, Bmax dropped to ≈45 mT, and finer litz; total loss rises to ≈37 W and efficiency falls to ≈98.77%. Although the core body shrinks to ~0.33×, the extra ≈9 W lands on a smaller surface, worsening heat-flux density and demanding extra cooling, while BOM cost rises — so neither overall density nor cost beats 400 kHz. That is the knee, demonstrated.

Mandatory Spec Checklist (400 kHz LLC transformer)

☐ **Frequency:** is there a topology/EMI hard constraint forcing 1 MHz? If not, lock 400–500 kHz.

☐ **Core material:** confirm at 400 kHz whether PC95/DMR95 meets loss and temperature rise; otherwise evaluate PC200 and cost/lead-time.

☐ **Gain & resonance:** are Lm/Lr/Cr solved jointly with gain curve, FM range, and light-load ZVS?

☐ **Winding:** does the secondary use litz/planar to keep Fr ≤2? Do strands/Cu thickness meet current and temperature rise?

☐ **800 V insulation:** do primary-secondary/interlayer withstand, creepage, and clearance meet the target safety class?

☐ **Thermal boundary:** does ΔT stay within Curie and insulation red lines? Is the hotspot located and dissipated?

☐ **Prototype:** are all order-of-magnitude estimates confirmed by sample testing (core loss, temp rise, Fr, insulation)?

07 FAQ

Q1: If 1 MHz makes the core smaller, why not just design at 1 MHz for ultimate density?

Because a smaller core does not equal a denser system. At 1 MHz core loss rises exponentially as f^α; you must switch to PC200-class specialty material and sharply lower Bmax to control it, which locks the room to shrink. The extra loss also lands on a smaller surface, worsening heat-flux density and demanding extra cooling that takes back volume. Counting core + cooling + winding, the real density of a 1 MHz design often does not beat 400 kHz, yet it carries several times the material cost and supply-chain risk.

Q2: For a 3 kW / 800 V LLC transformer, flat wire or litz?

It depends on frequency and current. At ≤200 kHz with moderate current, flat wire is fine; but at 400 kHz with a high secondary current (≈62.5 A), the high-frequency AC-resistance factor Fr of a thick solid or wide-edge flat wire rises markedly (up to 3–5) and winding loss overtakes. The secondary should then use multi-strand fine litz (single strand on the order of ≤2× skin depth), or evaluate a multilayer-PCB planar winding at moderate current.

Q3: Is the knee always 400–500 kHz? Does it shift with power or voltage?

The knee location moves with power, voltage, current, cooling conditions, and material system; 400–500 kHz is the typical sweet spot for the 3 kW class on an 800 V platform. At higher power and current, winding loss weighs more and the knee may move lower; with better materials (PC200-class) or stronger cooling, it may move higher. This article gives a criterion and method, not a universal fixed number — each project should locate its own knee through loss breakdown plus prototype testing.

08 Related Resources & Contact

ProMagTech specializes in custom design of high-current power inductors and transformers — covering flat-wire power inductors, PFC inductors, planar transformers, and toroidal power inductors — serving 800 V platform applications such as AIDC HVDC, energy-storage PCS, and EV fast charging. If you are evaluating a magnetics solution for a specific frequency/power/voltage combination, share your operating conditions and our engineering team will provide a targeted assessment.

Contact ProMagTech Engineering

For custom magnetics design support, share your operating conditions with our engineering team:

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Disclaimer: All quantitative figures in this article (loss, efficiency, volume, temperature rise, turns, material parameters, etc.) are order-of-magnitude estimates based on public industry references, the Steinmetz material model, and standard engineering assumptions. They illustrate the frequency–loss–volume trend and the knee criterion, do not represent measured data of any specific product, and constitute no performance guarantee. Actual designs must be confirmed by project prototype testing. Material parameters (Bs, Curie temperature, skin depth, insulation class, etc.) are public reference values requiring project confirmation.