PROGEN

Development of Cobalt-Based Amorphous Alloy Systems for Ultra-Low Permeability Magnetic Core Applications

Advancing High-Frequency, High-Temperature Nanocrystalline Materials

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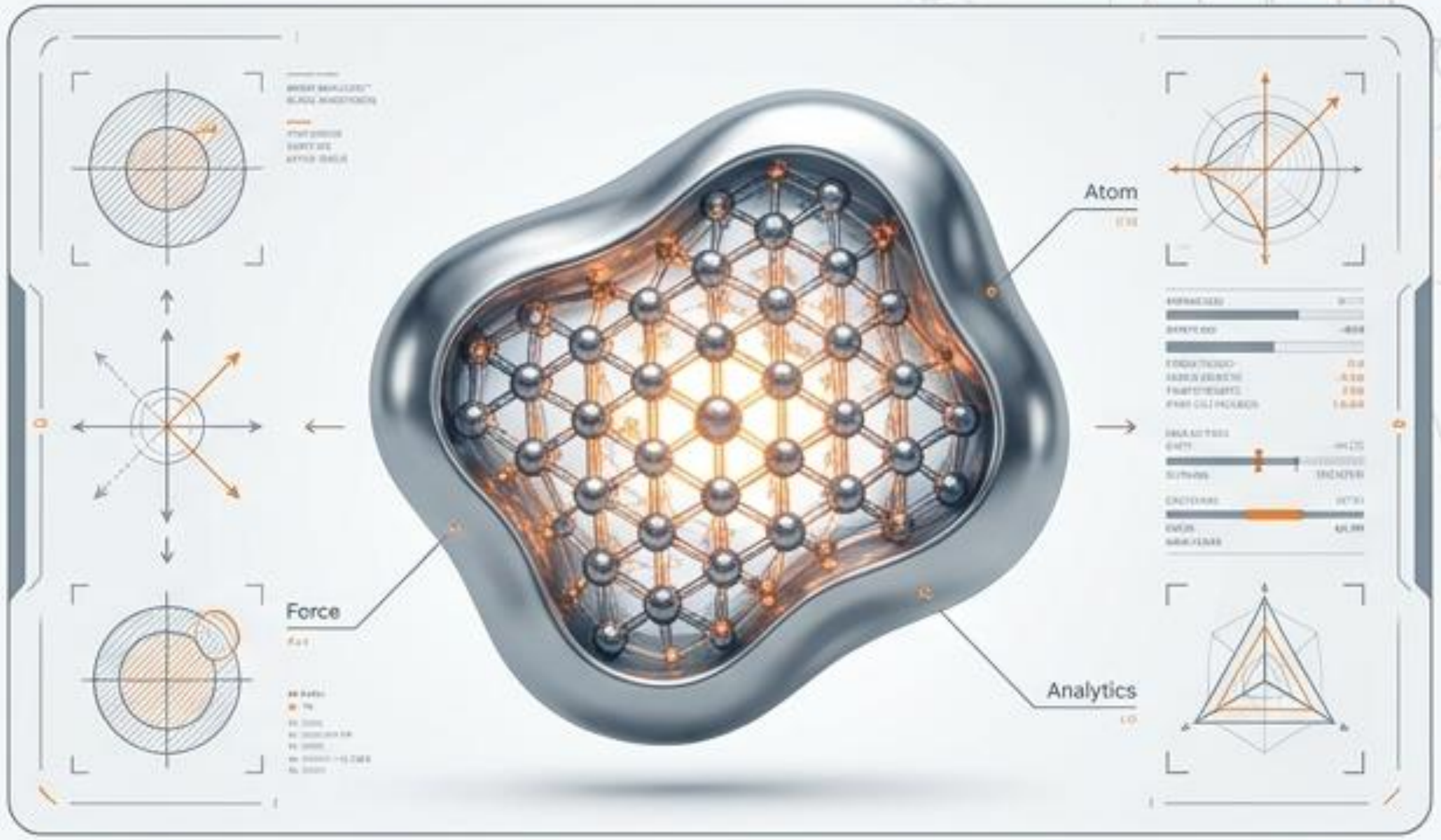
The Quest for Ultra-Soft Magnetism



Key Insight Panel

Achieving a coercivity (H_c) < 1 A/m, reaching magnetic saturation merely by exposure to the Earth's ambient magnetic field (~40 A/m).

Extreme sensitivity is the defining characteristic of amorphous metallic glasses and iron-based nanocrystalline alloys, rendering them the ultimate candidates for high-efficiency energy sincy energy s

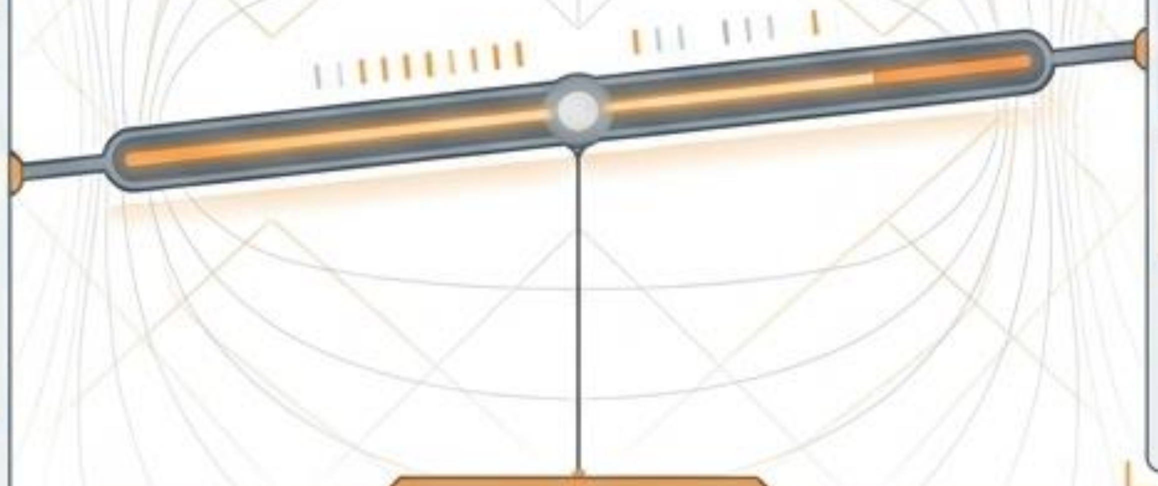
The High-Frequency Paradox

High Frequency & Low Permeability

$$E = \frac{B^2 V}{2\mu_0 \mu}$$

$$\frac{P_{\text{core}}}{V} = k_s f^{\alpha} B_m^{\beta}$$

Maximizing stored energy and minimizing core loss requires driving the effective permeability (μ) as low as possible.



Low Copper Loss & High Permeability

$$P_w = RI^2$$

Achieving sufficient flux density (B) without excessive winding necessitates a high permeability (μ).

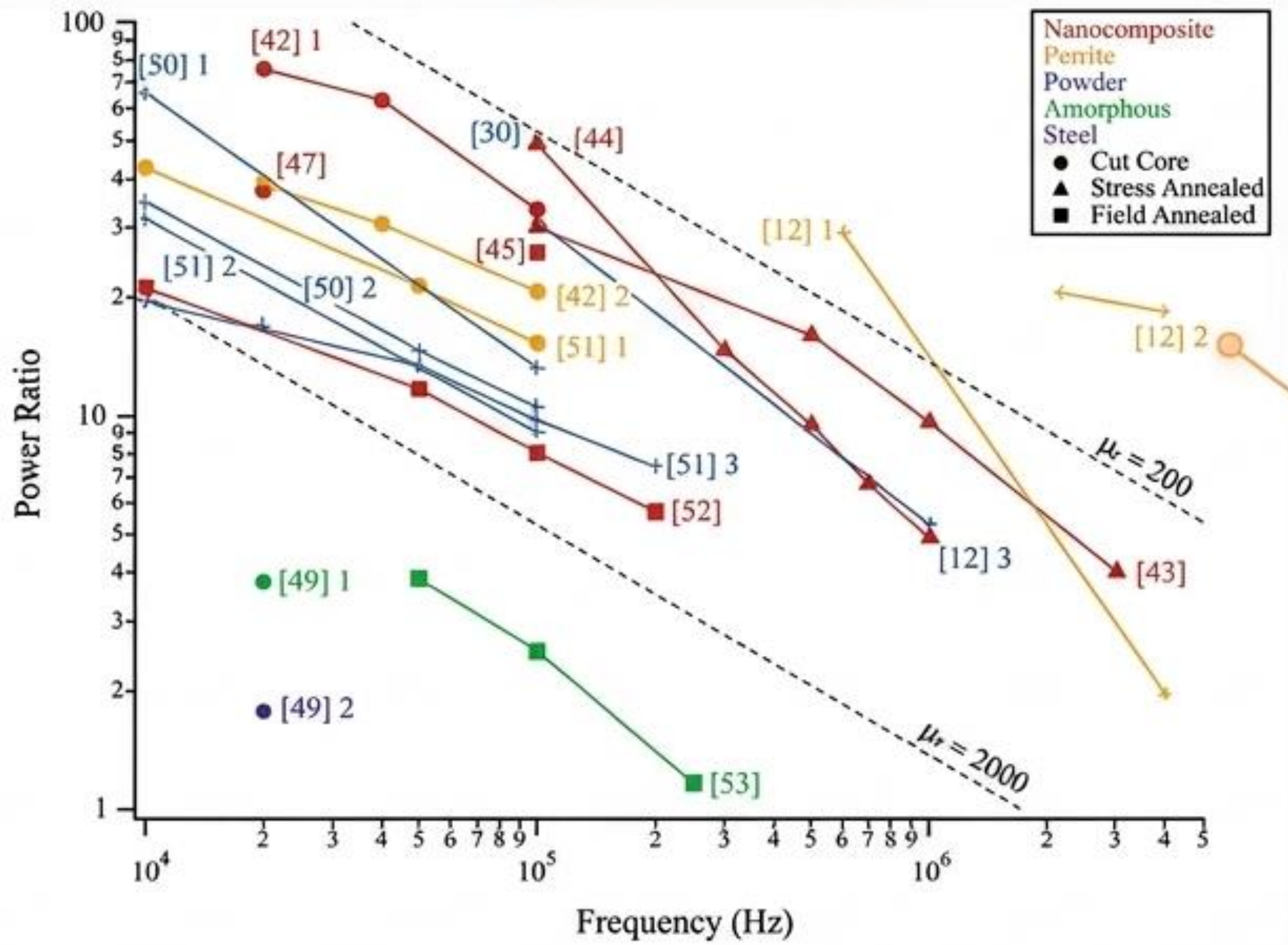
Anchor

$$\mu_{\text{opt}} = \left(\frac{RN^2 k_s V f}{\dots} \right)^{1/2}$$

Diagnostic

The engineering imperative is to hit the exact theoretical optimum. Success dictates perfectly designable, ultra-low permeability materials.

Mapping the Power Ratio Figure of Merit

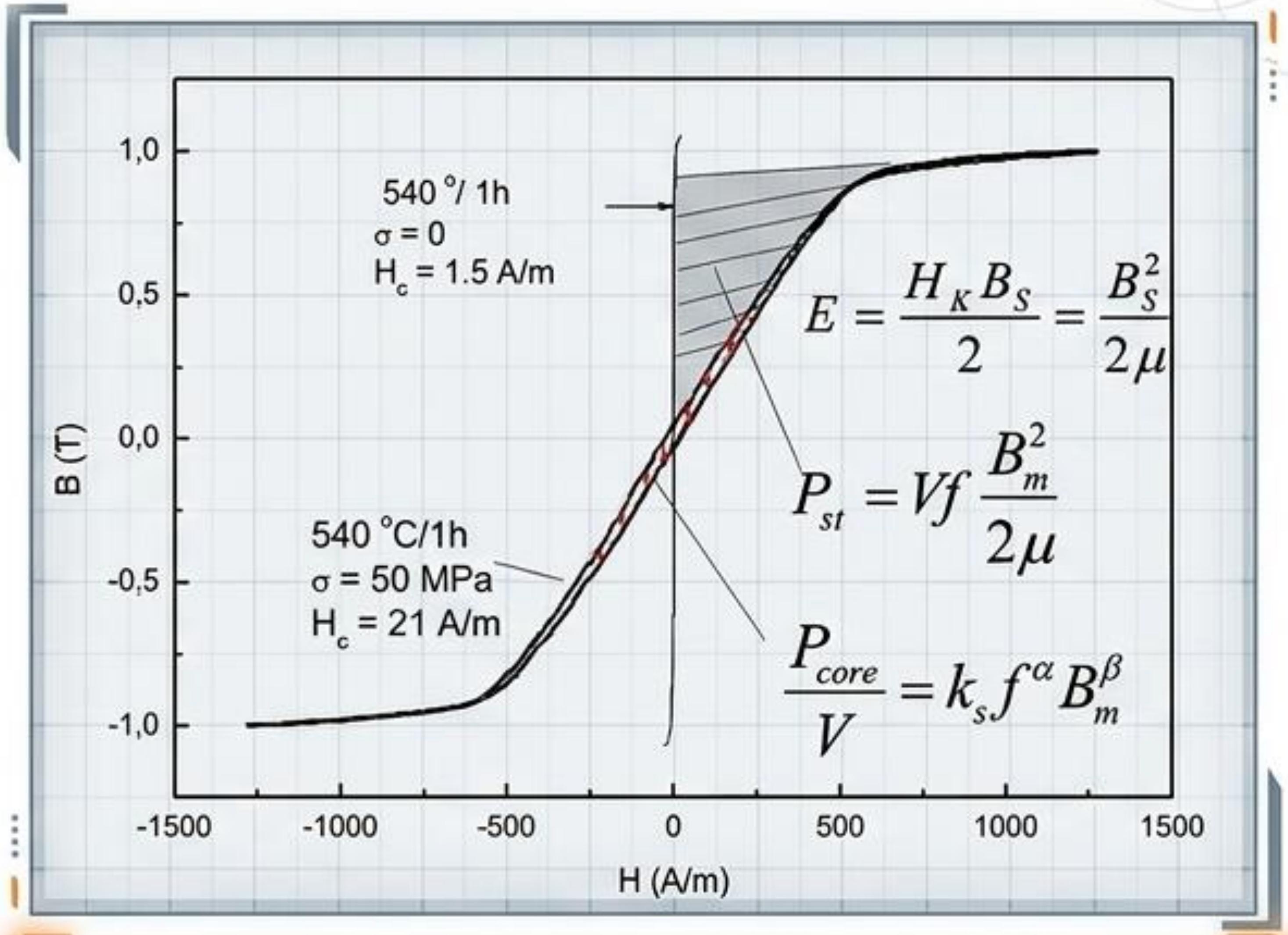


$$P_{ratio} = \frac{P_{stored}}{P_{loss}}$$

Lower permeability allows the material to maintain a Power Ratio > 10 at significantly higher frequencies compared to standard ferrites and powder cores.

Volume Scaling and Permeability Design

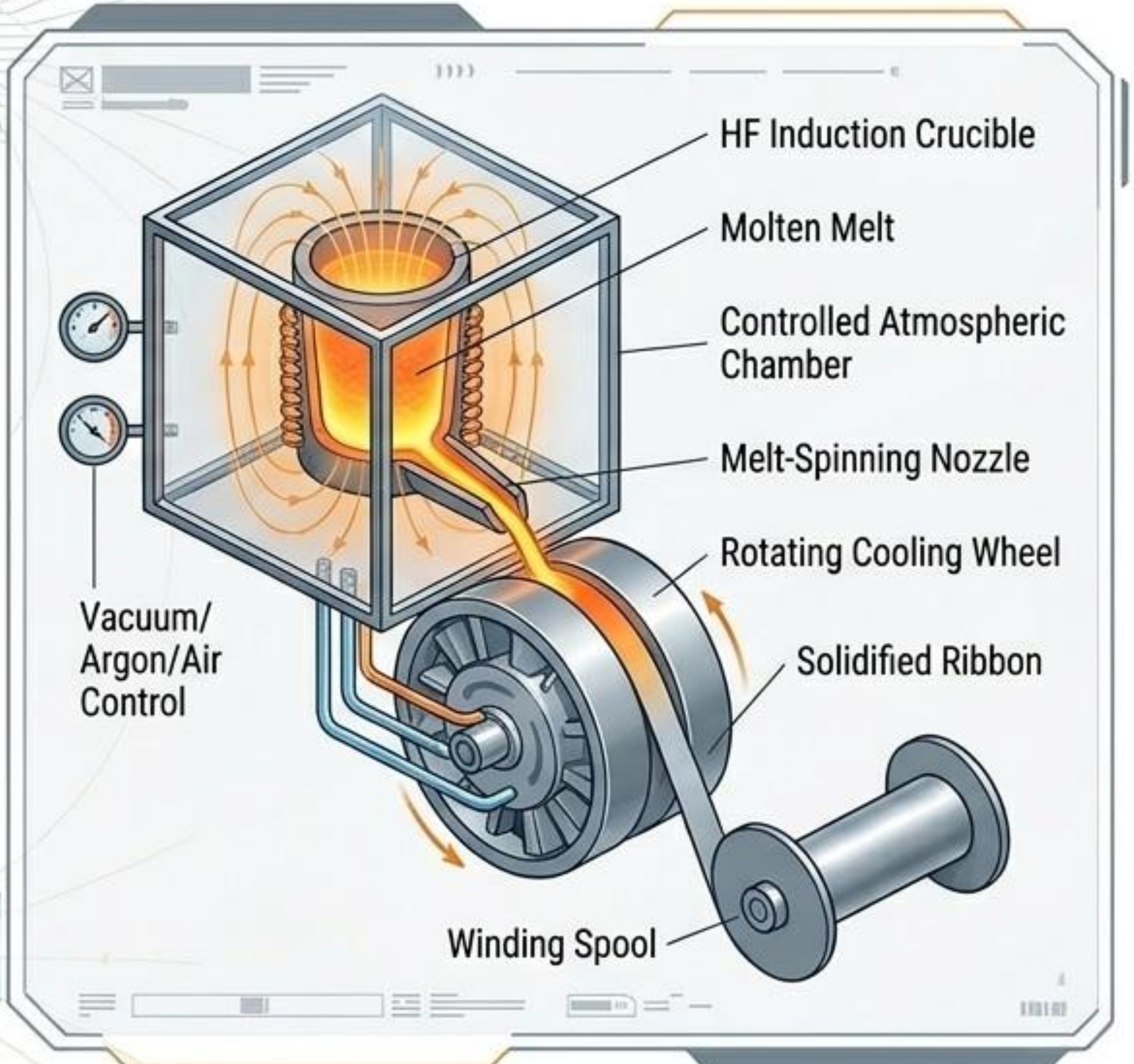
$$\frac{\mu_{eff}}{V} = \frac{B_p^2}{\mu_o \cdot L \cdot I_p^2}$$



For a given stored inductive energy, the core volume must scale synchronously with permeability.

Stress annealing creates the linear, flattened B-H curve required to hit the precise permeability target without sacrificing volume efficiency.

Experimental Synthesis: Planar Flow Casting



1. High-frequency magnetic induction melting

2. Precise atmospheric control (Vacuum, Argon, Air)

3. Rapid melt-spinning onto a cooling wheel

Critical Parameter Readouts

Wheel surface speed: [VALUE] m/s

Melt temperature: [VALUE] °C

Holding time: [VALUE] min

Capillary-wheel gap: [VALUE] μm

Impingement angle: [VALUE] °

The Silicon Doping Shield

Silicon doping facilitates air-casting by forming a protective complex amorphous oxide layer on the ribbon surface, preventing bulk oxidation and providing inter-layer insulation.

Evolving the Fe-Based Finemet Architecture

Boron Reduction

Decreasing B in favor of Si. Decreases thermal stability but raises the Curie temperature of the residual amorphous phase to **380°C**.

Iron Reduction

Decreasing Fe in favor of Si. Pushes crystallization onset to **549°C** while maintaining optimal coercivity, but offers no cost reduction.

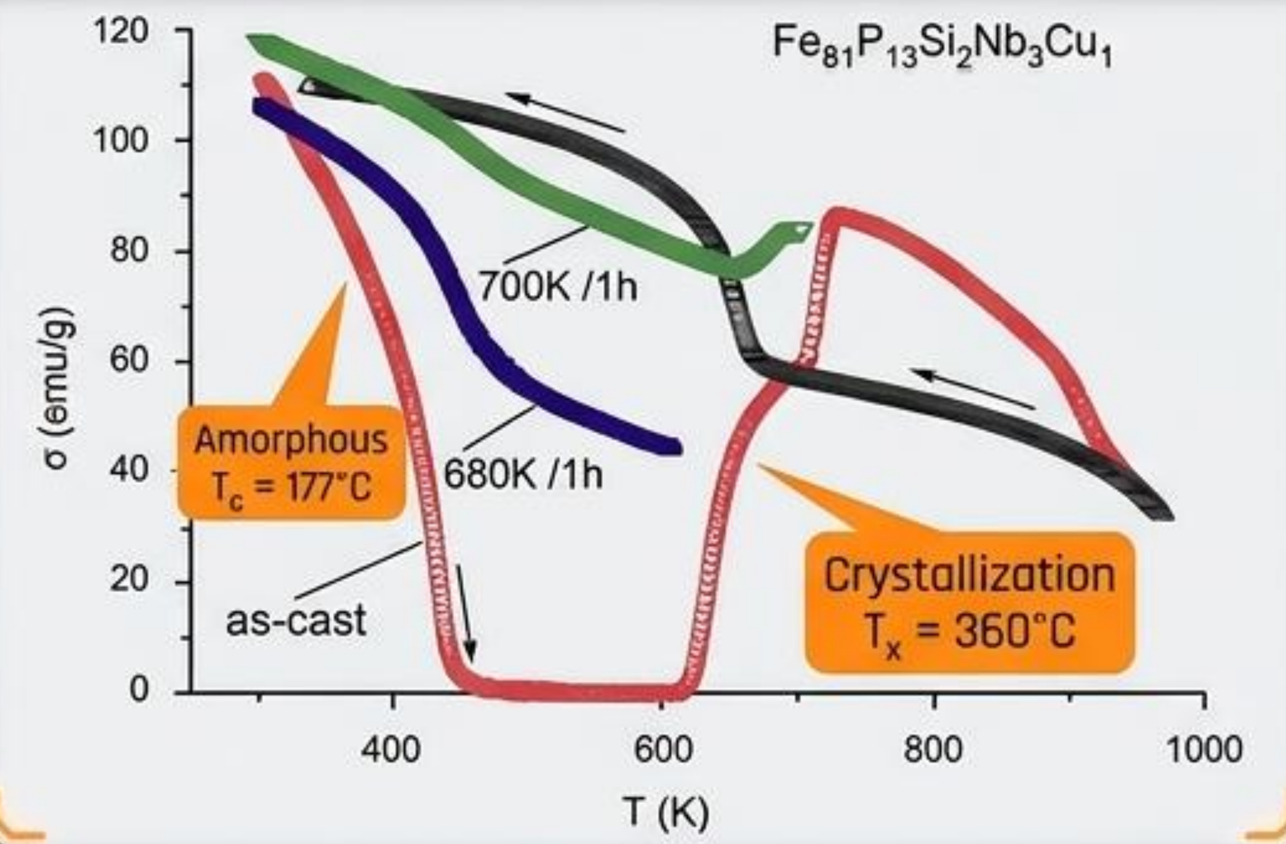
The Phosphorous Substitution

Swapping Boron for Phosphorous. A strategic move replacing an expensive metalloid with highly economical ferro-phosphorous.

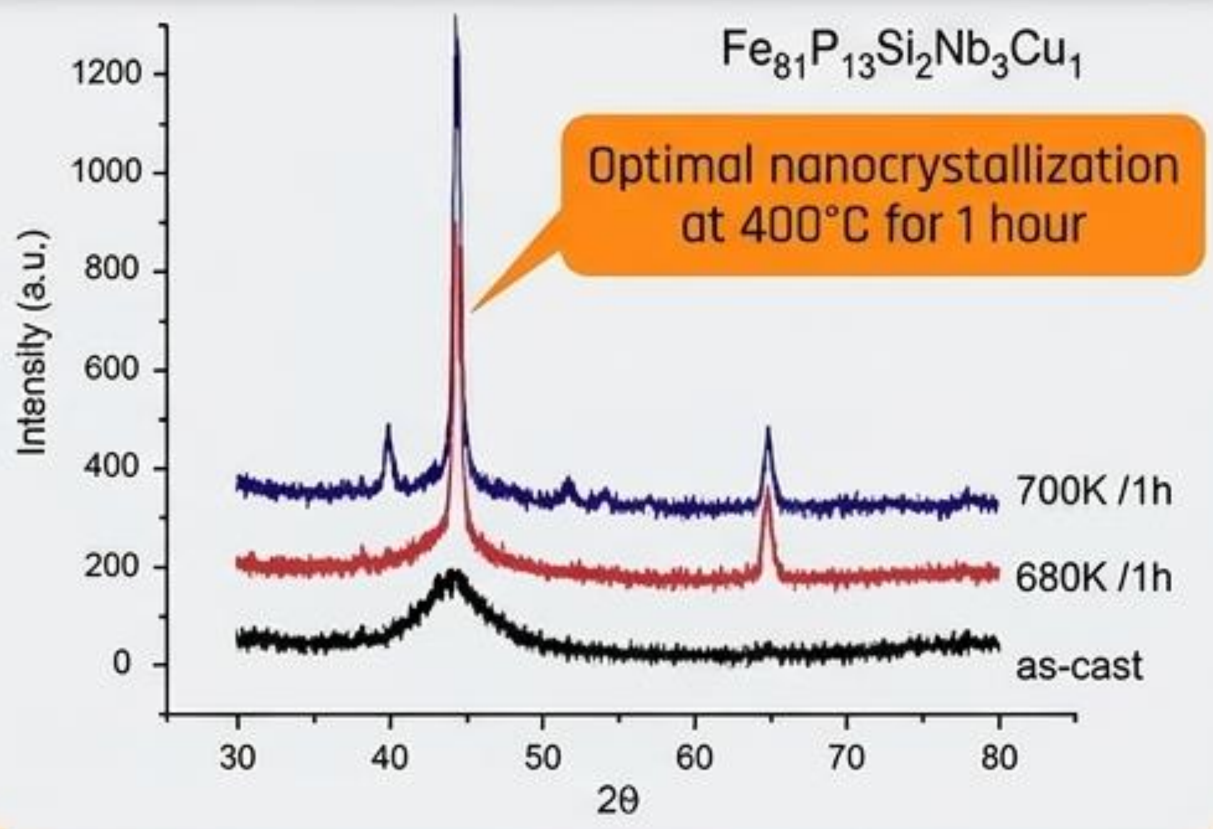
Structural & Magnetic Profile: The Phosphorous Variant

$Fe_{81}P_{13}Si_2Nb_3Cu_1$

THERMO-MAGNETIC ANALYSIS



XRD DIFFRACTION SPECTRA



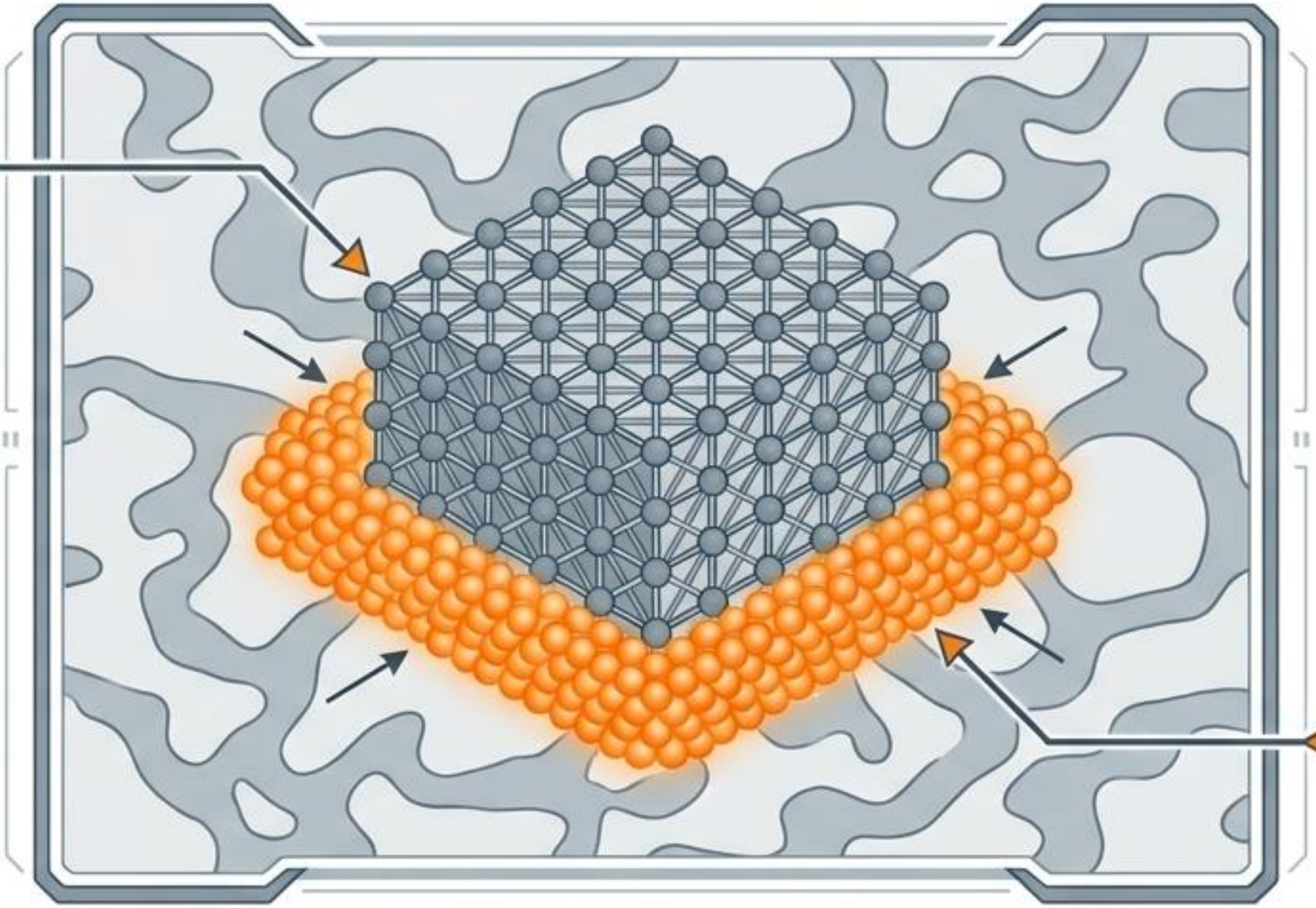
Saturation: Bs = 1.1 T

Coercivity: Hc = 35 A/m

Status: Within technically acceptable limits but requires further alloy refinement.

Nanocrystallization Kinetics: The Soft Impingement Model

Primary nanocrystals precipitate from the amorphous matrix.

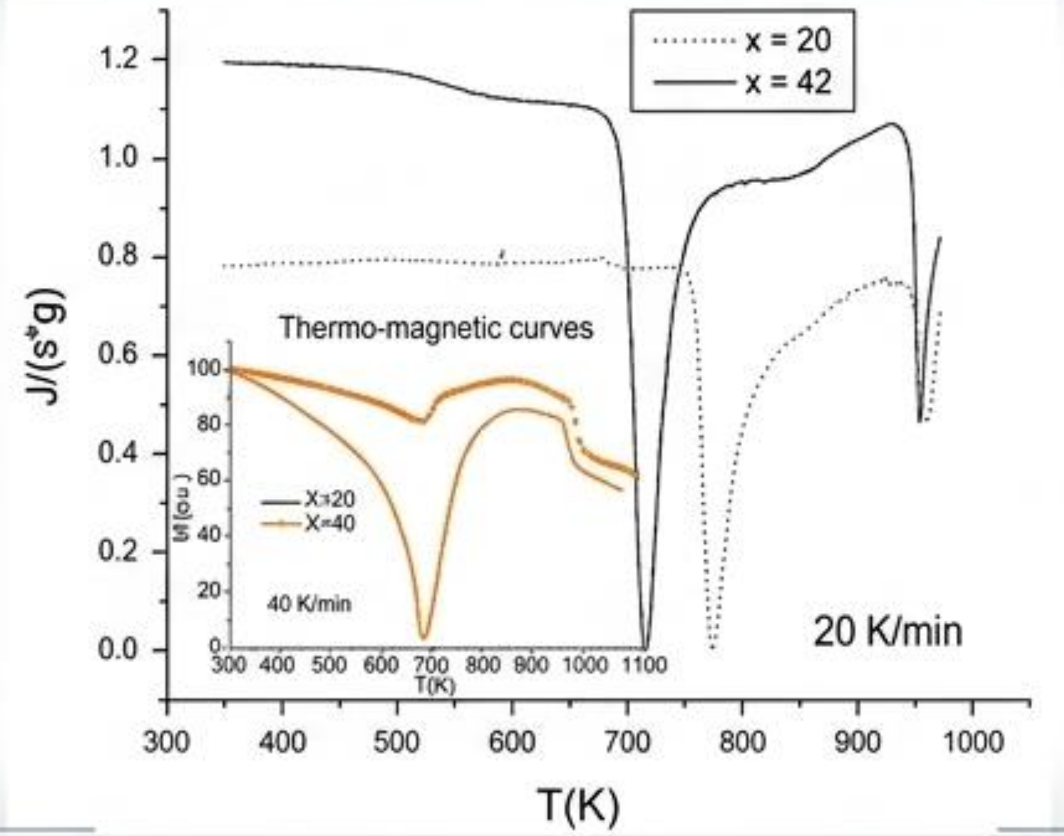


Early Transition Metals (Nb, Zr) segregate into the residual phase, forming a dense diffusion barrier shield.

This physical barrier halts further grain growth precisely at the nano-scale, creating the requisite nanostructure without thermal runaway.

Cobalt-Dominated Systems: Introducing Pyroperm

$$Fe_{85-x}Co_xNb_5B_8P_2$$

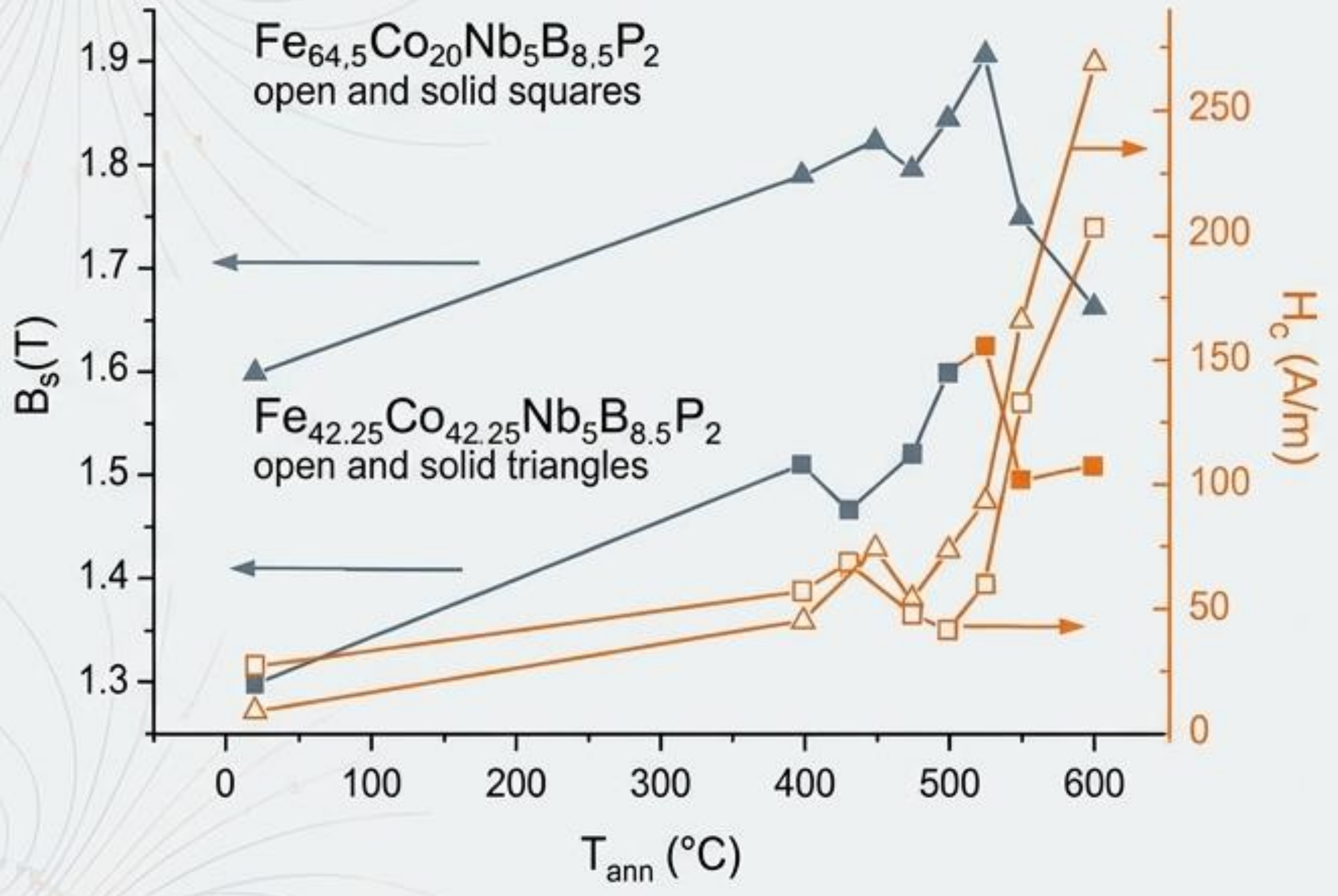


x = 20 Variant
Crystallization (T_x) = 500°C
Curie temp (T_c) = 400°C

x = 40 Variant
Crystallization (T_x) = 442°C
Curie temp (T_c) > Crystallization temp

Permeability remains completely independent of temperature, unlocking new capabilities for high-temperature automotive applications.

Magnetic Stability Across Thermal Regimes



Saturation (Bs)

Reaches an impressive **1.65 T**, approaching the capabilities of traditional Fe-Si steel.

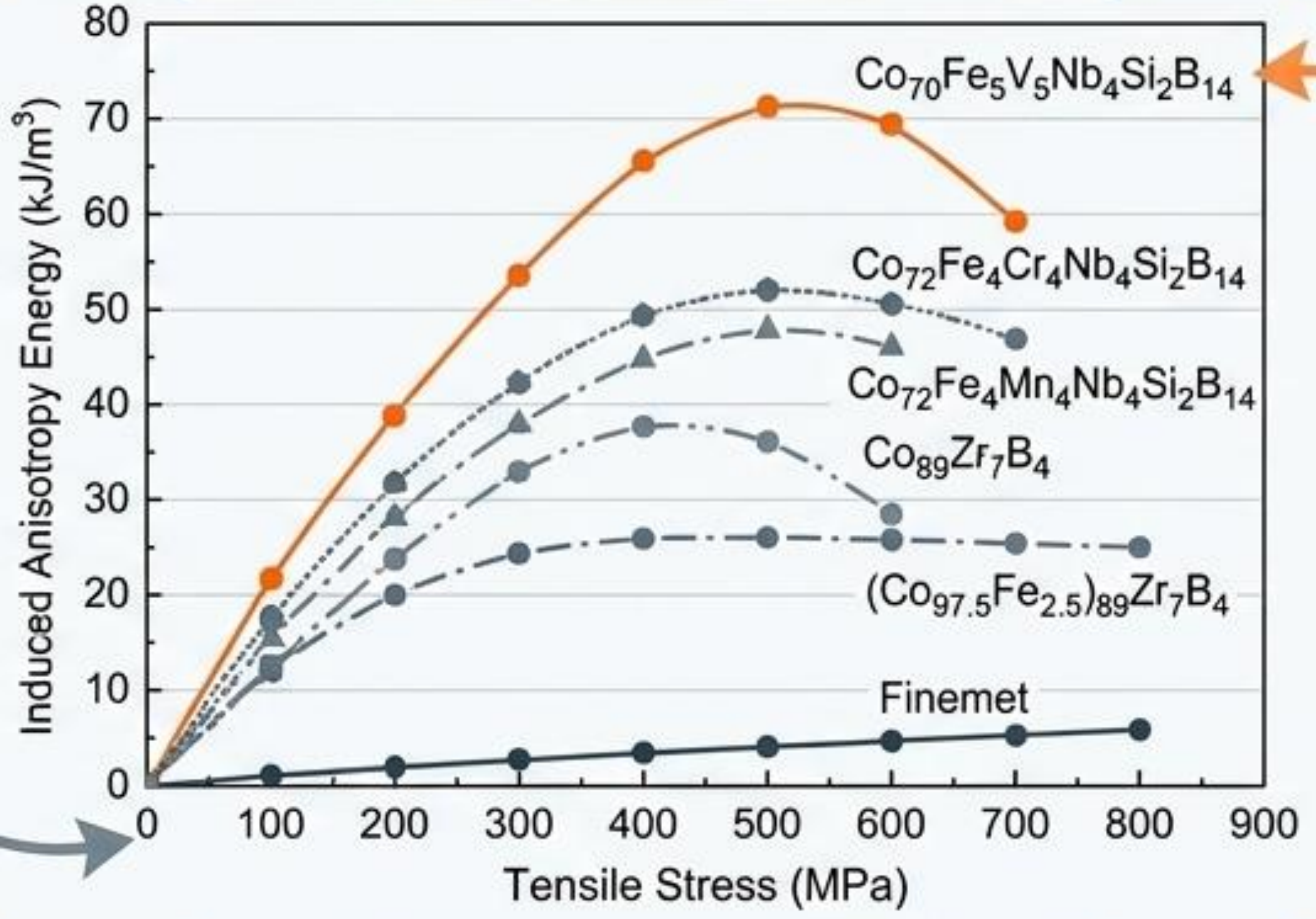
Coercivity (Hc)

Stabilizes around a steady **40 A/m**.

Thermal Resilience

Starting permeability (**~450**) and coercivity remain strictly independent of applied annealing temperatures up to **525°C**.

Giant Strain-Induced Anisotropy in Co-Rich Alloys



Co-Rich Alloys: Massive anisotropy spike generating > 70 kJ rJ/m³ at 500 MPa.

Fe-Rich Alloys: Minimal anisotropy gain under applied stress.

This immense **stored magnetic energy** capacity directly rivals the structural energy found in **permanent Neodymium magnets**.

The Physical Mechanism: FCC vs. HCP Transformation

Literature Model (McHenry Group)

Proposes FCC cobalt nano-precipitates.

Anisotropy is driven by high packing fault densities possessing HCP-symmetry.

Triggered by Early Transition Metal Virtual Bound States (VBS).

PROGEN Hypothesis

Proposes direct formation of **pure HCP nano-cobalt precipitates** under **tensile stress**.

Early Transition Metals act to **stabilize the FCC phase**.

Small alphagenic atoms (C, B) act to **stabilize the HCP phase**.

Component Validation: Powder Cores vs. Ribbon-Wound Toroids

Metric	Industry Powder Core	Ribbon-Wound Toroid
Saturation (Bs,max)	~ 1 T	**> 1 T**
Coercivity (Hc)	~ 60 A/m	**< 10 A/m**
Source of Low Permeability	Shape Anisotropy	Induced Anisotropy
Linearity	Moderate	Excellent

Cobalt-based toroids fundamentally **bypass the limitations of shape anisotropy**, offering **superior linearity** and **minimal losses**.

The Blueprint Realized: Precision Magnetic Energy

Theoretical optimums transformed into physical reality through advanced **Co-rich alloy design**.

Soft impingement kinetics and **Giant Strain-Induced Anisotropy** completely decouple permeability from temperature.

A newly established industrial pathway designed for **high-frequency, extreme-temperature** inductive applications.

PROGEN R&D. Data, methodologies, and characterization ready for peer discussion.

The Physical Imperative for Ultra-Low Permeability

The Paradox of High-Frequency Magnetic Energy Storage

To maximize stored energy independent of DC bias, relative permeability must be minimized, and the hysteresis curve must remain linear up to saturation.

Magnetic Energy Storage:

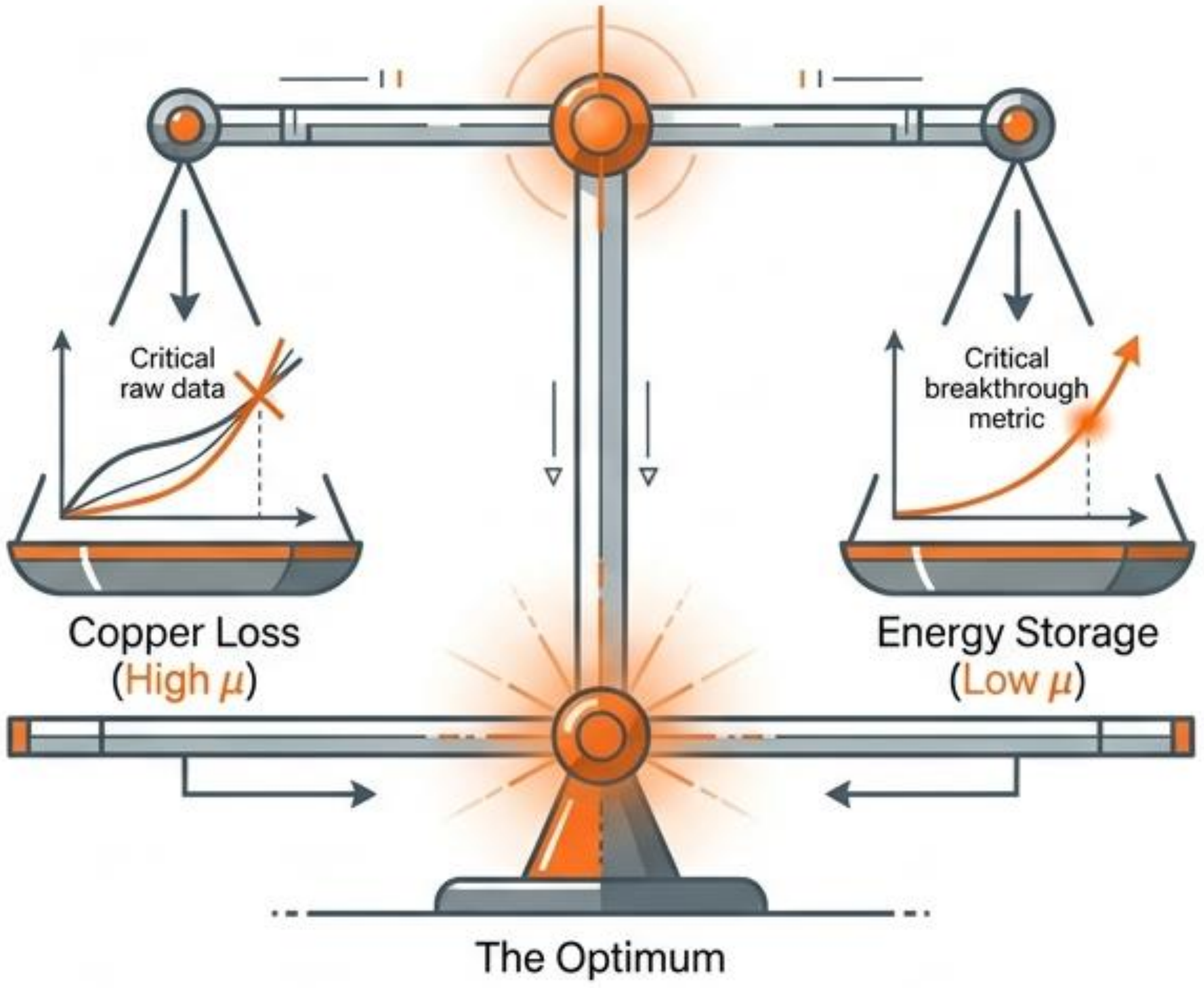
$$E = \frac{B^2 \cdot V}{2\mu_0 \mu}$$

(Lower effective permeability = Exponentially higher stored energy)

The Core vs. Copper Trade-off:

- **Low Permeability:** Essential for high-frequency operation and exponentially scaling high energy storage.
- **High Permeability:** Traditionally required to minimize copper loss (requiring fewer windings for a high B-field).

The Engineering Challenge: Finding the precise permeability optimum for specific high-frequency topologies.



Strategic Approach to High-Frequency Cores

Overcoming the Limits of Conventional Technologies

Existing high-frequency solutions face rigid physical constraints:

- **Powder Cores**: Require energy-intensive compaction and suffer from strict size limitations.
- **Ferrites**: Suffer from severe thermal limitations (max ~100-110°C) without losing soft magnetic properties.

The PROGEN Development Strategy

1. Material System

Design a novel Co-based metal-metal amorphous nanocomposite.

2. Form Factor

Utilize continuous ribbon formatting to eliminate size constraints and EMI/RFI radiation issues inherent to cut cores.

3. Phase Control

Apply specialized tension-annealing to induce controlled nanocrystallization, achieving precise ultra-low relative permeability.

Material System & Macroscopic Validation

From Pre-Alloy to Controlled Microstructure

The material development relies on rapid quenching techniques followed by highly precise thermal profiling.

The Macroscopic Mechanical Proxy: 180° Bend Testing

Conclusion: This binary mechanical behavior serves as an immediate, high-confidence pre-qualification tool verifying the success of rapid quenching and the readiness for thermal treatment.

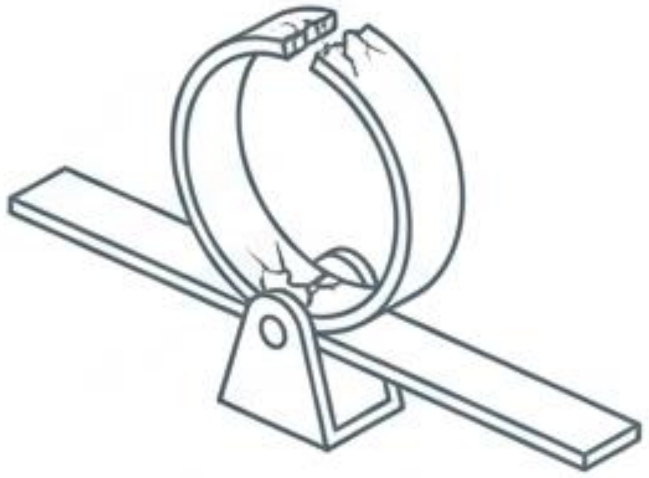
180-degree Bend Test

Scenario A

Fully Amorphous State

Lacks long-range order. Endures 180° bend without fracturing.

Scenario B



Crystalline State

Dislocation pile-ups cause immediate fracture upon bending.

Selection of the Co-Based Alloy System

Following extensive Design of Experiments (DOE), a proprietary Cobalt-based alloy was selected for final prototype advancement.

Key Selection Criteria Achieved:

Homogeneity

Excellent ribbon drawability with minimized edge defects (critical for automated winding).

Thermal Responsiveness

Highly predictable nanocrystallization under applied mechanical stress.

Magnetic Baseline

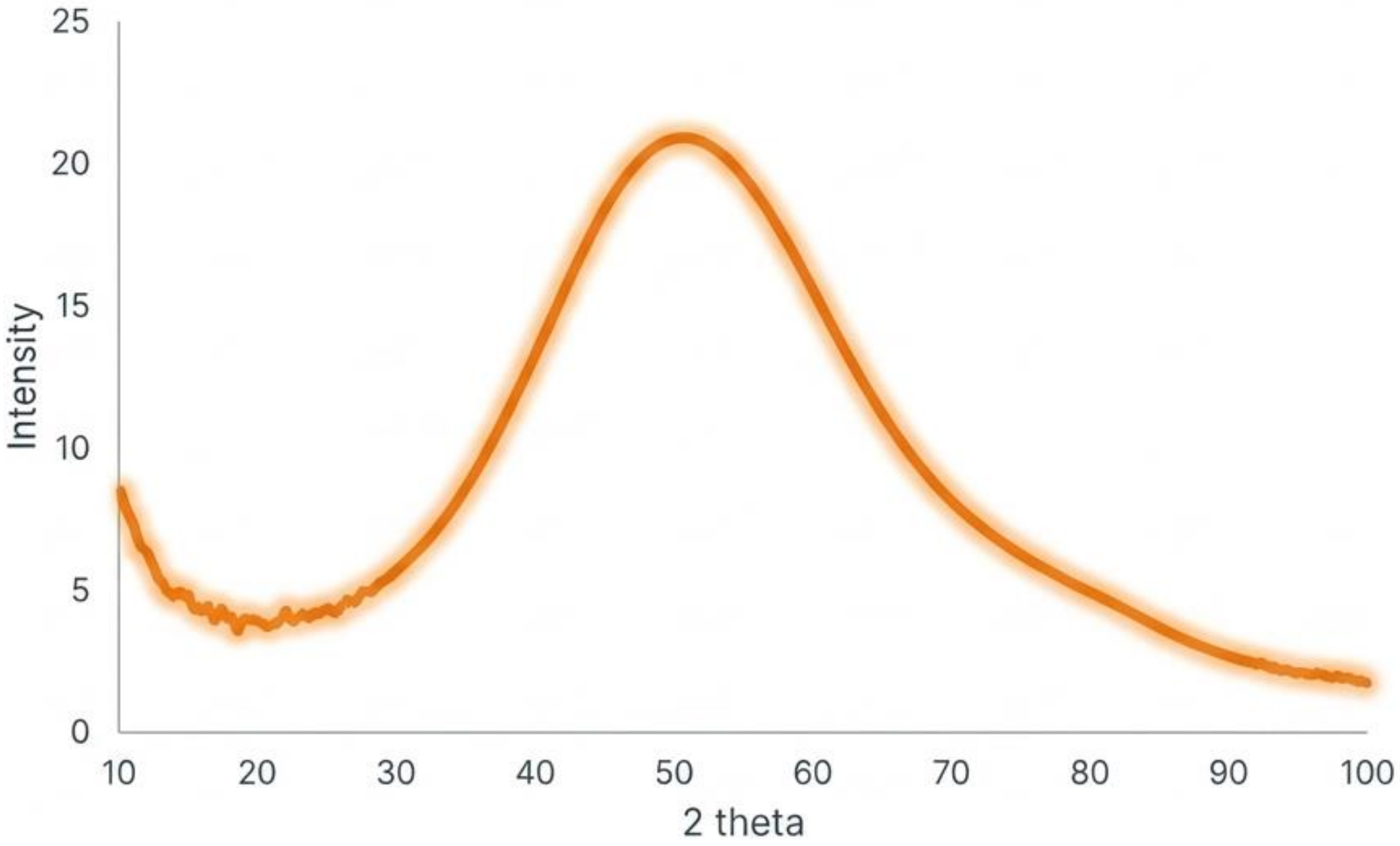
Superior soft magnetic properties compared to Fe-based alternatives, especially at elevated operating temperatures.

Outcome: The Co-based pre-alloy provides the optimal matrix for ultra-low permeability tuning via precision tension annealing.

Structural Validation: The Amorphous Precursor
X-Ray Diffraction (XRD) Analysis

Confirmed Amorphous Matrix

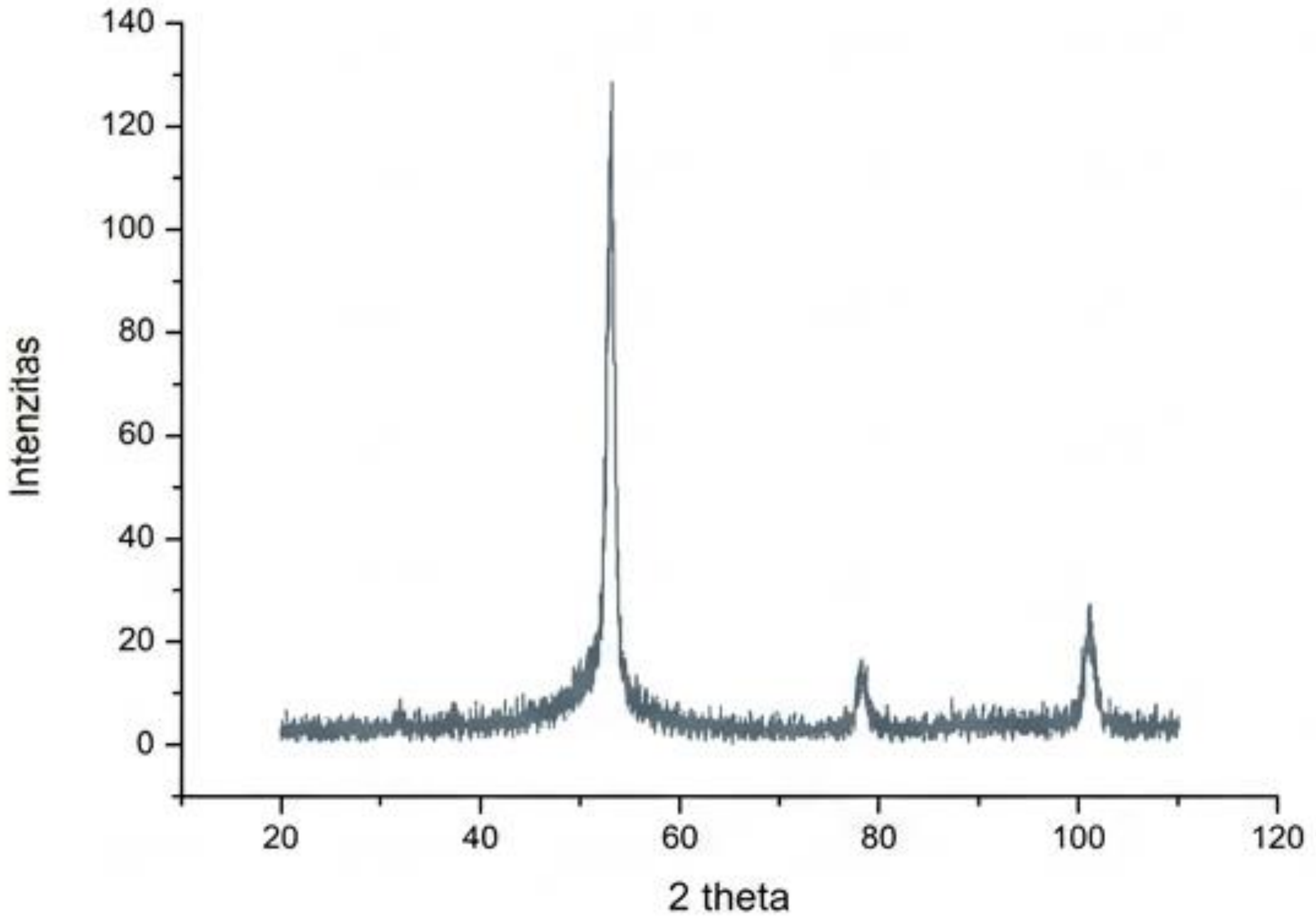
- The X-ray scattering profile demonstrates a complete absence of distinct crystallographic peaks.
- The characteristic broad 'halo' confirms the lack of long-range structural order.
- This fully amorphous state is the mandatory starting condition for successful subsequent permeability tuning.



Structural Validation: Controlled Nanocrystallization

By applying precise thermal profiles under mechanical tension, the amorphous matrix is partially crystarllized at the nanoscale.

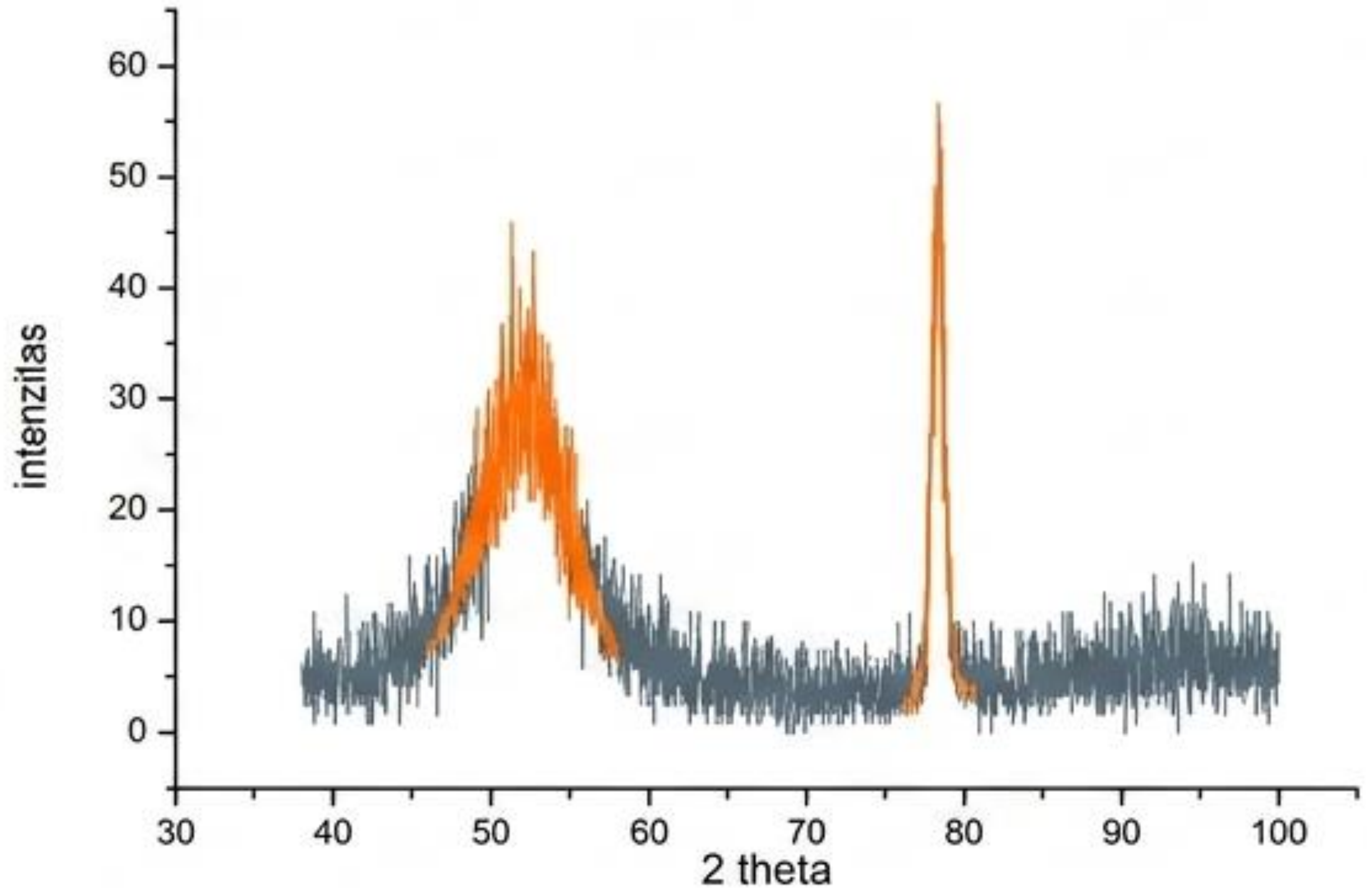
Fully Crystalline Reference



Crystalline Reference

- Sharp, high-intensity peaks indicate large grain sizes and complete crystallization (highly detrimental to soft magnetic properties).

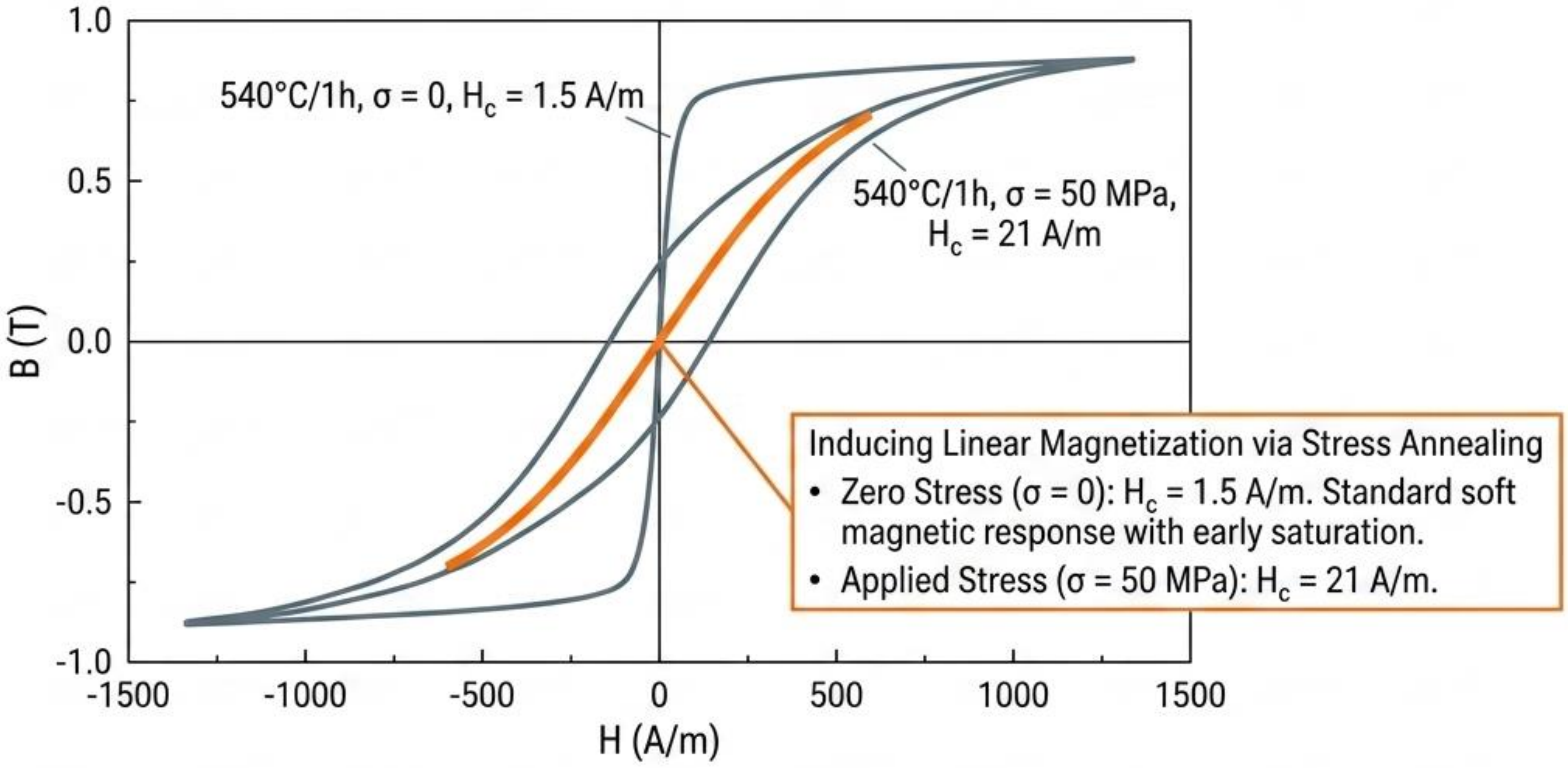
Target Nanocrystalline State



PROGEN Target State

- Broadened intensity peaks superimposed on the amorphous halo. The Full Width at Half Maximum (FWHM) confirms nano-scale grain sizing, yielding the desired ultra-low permeability.

Magnetic Validation: B-H Curve Linearity



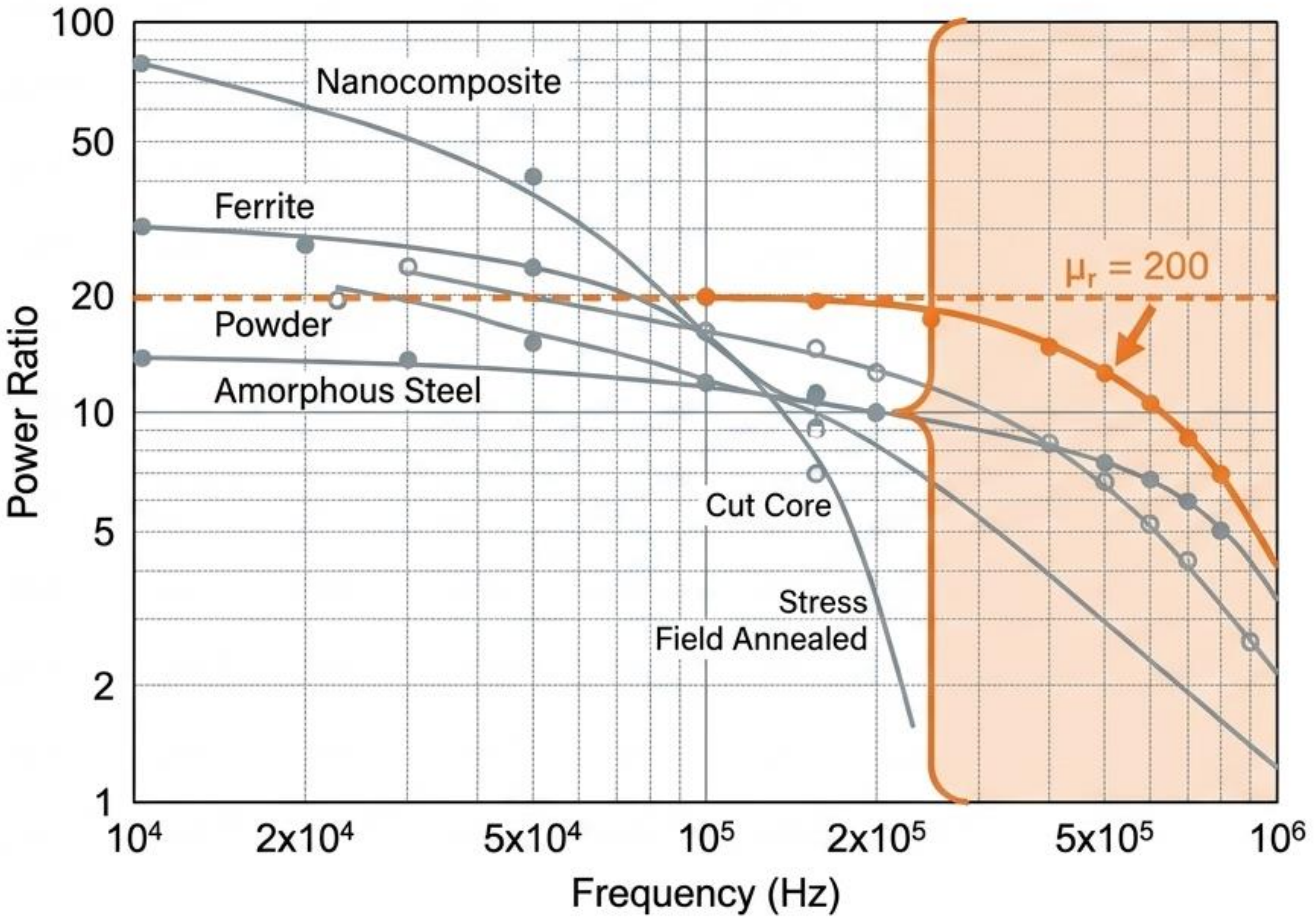
Observation: The appur application of 50 MPa of mechanical tension during the 540°C/1h thermal anneal effectively star shears the B-H curve. This generates the highly linear response strictly required for high-frequency energy storage applications.

Permeability Optimization vs. Power Ratio

$$P_{ratio} = \frac{P_{stored}}{P_{loss}}$$

Unlocking the High-Frequency Regime

- The graph maps the material Quality Factor (Power Ratio) across existing material families.
- **The Key Insight:** Lower relative permeability allows the material to maintain a Power Ratio >10 at significantly higher frequencies.
- PROGEN's Co-based cores are structurally tuned to operate in the ultra-low permeability regime (μ = 200), actively avoiding the steep loss drop-offs seen in standard high-permeability composites at frequencies $f > 100$ kHz.

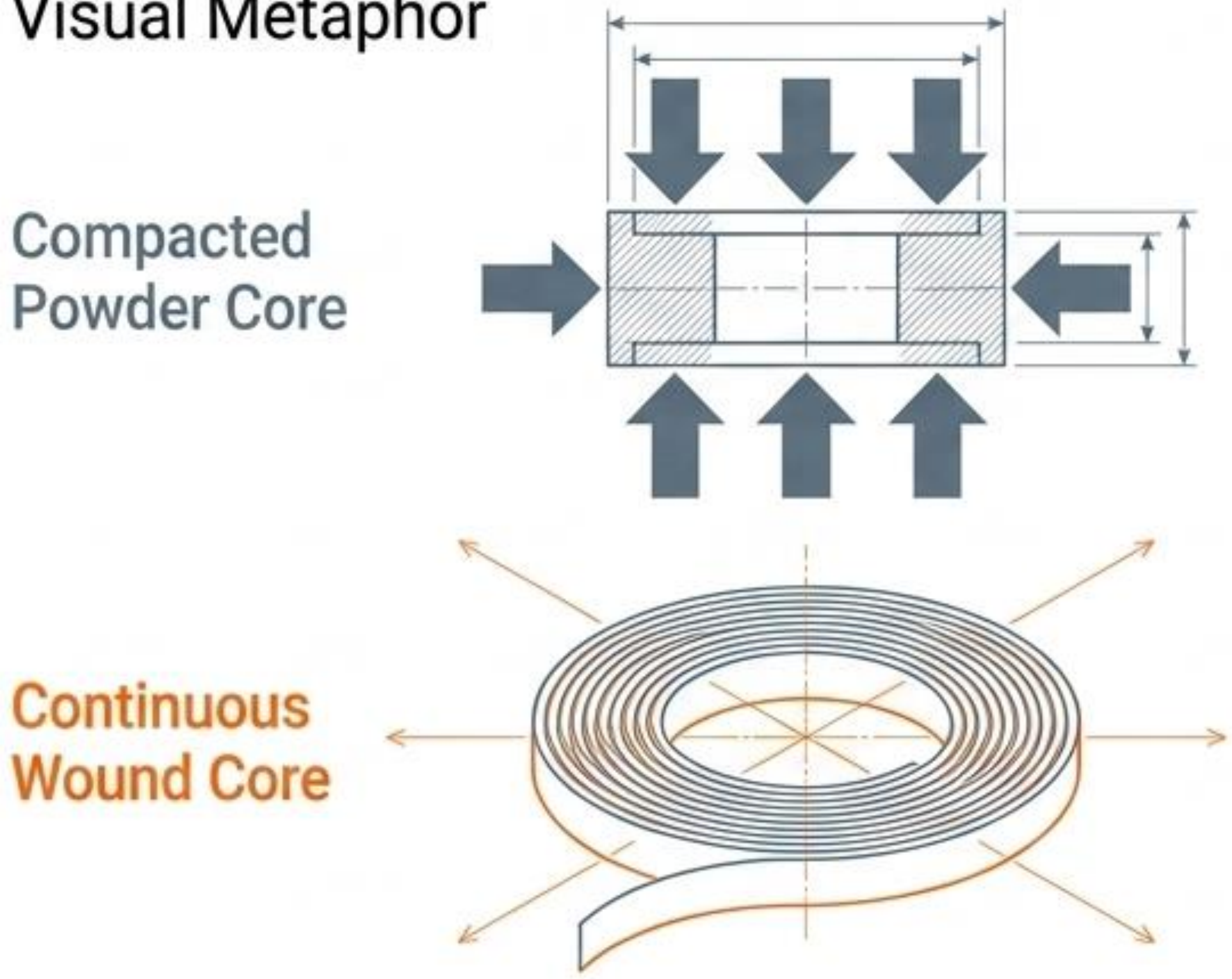


Form Factor: Continuous Wound Toroidal Cores

Continuous Ribbon Winding Methodology

Transitioning from material phase control to component architecture, the tension-annealed Co-based ribbon is wound into closed toroidal cores.

Visual Metaphor

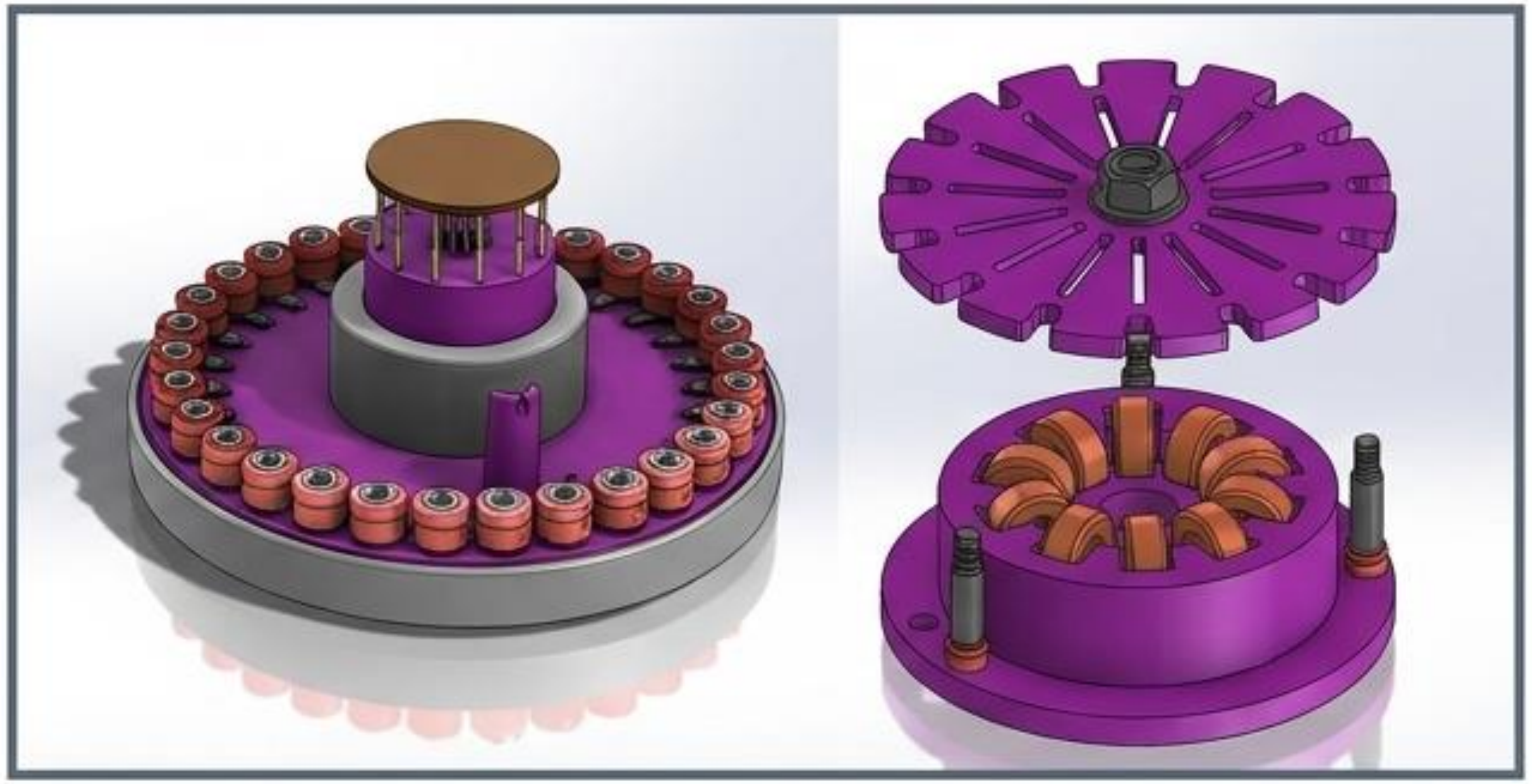


Structural Advantages over Market Standards

- **No Size Limitations**: Powder cores require massive compaction presses restricting them to ~125mm maximum outer diameters. Wound ribbons allow arbitrary, infinitely scalable core sizing.
- **Zero Gap Radiation:** Unlike cut cores, the closed wound toroid naturally eliminates EMI/RFI radiation leakage.
- **Economic Manufacturing:** Wholly bypasses the capital-intensive and high-energy compaction processes required for competitor powder cores.

High-Frequency GaN FET Measurement Architecture

To validate prototype performance under real-world conditions, standard measurement equipment was insufficient. Custom modular testing methodologies were engineered.



Test Architecture Highlights:

- EPC9083 Class E Amplifier: Engineered for high-efficiency, differential evaluation up to an extreme **15 MHz** operating frequency.
- EPC9084 Half-Bridge: Capable of **350V** max voltage and **4A** output current.
- Modular Fixtures: Custom 3D-designed test fixtures guarantee controlled, repeatable parasitic capacitance and inductance baseline profiles.

Statistical Reliability and Methodological Calibration

Cross-Validation of Permeability Measurement Methods

Robust statistical analysis was performed across a large batch of core prototypes using both RLC meter and B-H meter methodologies to ensure commercial viability and absolute data integrity.

Intra-Method Variance

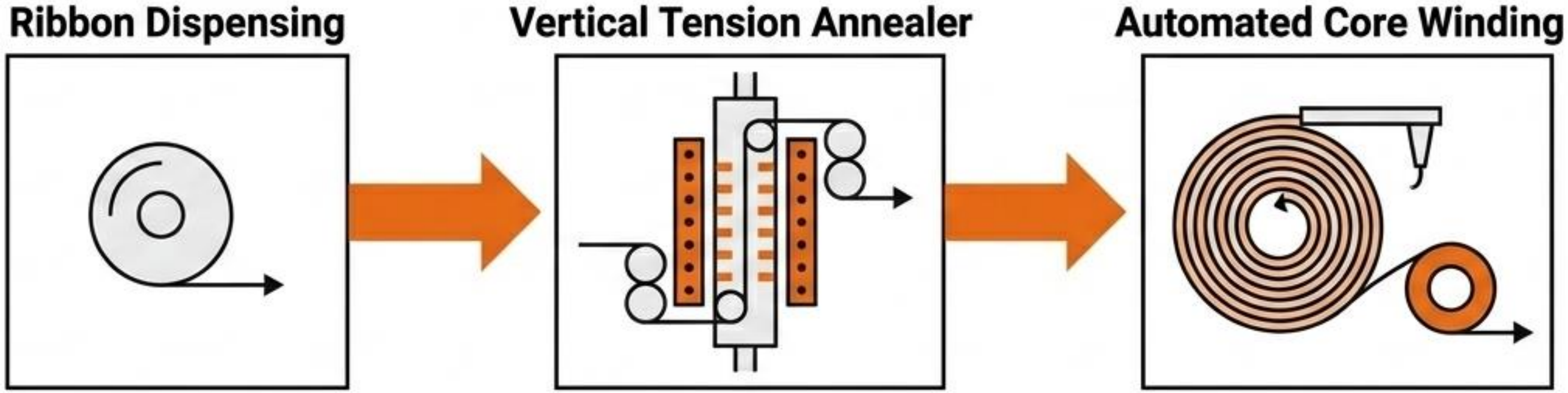
Inter-Method Variance

- **Intra-Method Reliability:** Permeability measurements using the identical method yielded a variance of < 1%.
- **Inter-Method Variance:** Measurements cross-calibrated between the RLC and B-H methodologies yielded a maximum difference of just 7%.
- **Parasitic Isolation:** 1-turn baseline measurements exhibited superior statistical tightness compared to 15-turn tests, successfully isolating parasitic capacitive effects introduced by the copper windings.

Scalable Manufacturing Technology

Integration of Annealing and Winding Systems

A semi-industrial prototype manufacturing line was engineered to ensure the continuous, reliable production of the Co-based cores.



Key Technological Parameters Achieved:

- Automated Toroidal Winding Unit: Successfully integrated into a continuous flow with a vertical, under-tension annealing unit.
- Yield Optimization: The automated system achieves excellent yield and negligible error rates for toroidal cores with outer diameters >30 mm.
- Geometric Stability: Ribbon width mapping definitively indicated that 20 mm wide ribbons result in optimal tracking and vastly lower winding fault rates compared to narrower configurationconfigurations

Industrial Benchmark and Market Relevance

The PROGEN Co-based core breaks the physical constraints of current market leaders by uniting high thermal stability, high frequency capability, and unlimited core geometry.

Material Technology	Maker	Permeability (μr)	Max Temp	Max Freq.	Size Limits
MPP Powder	Magnetics Ltd	14 - 300	200 °C	2 MHz	Yes (Max 125mm)
Kool Mμ MAX	Magnetics Ltd	26 - 60	200 °C	900 kHz	Yes
Type 67 Ferrite	Fair-Rite	10 - 100	110 °C	20 MHz	Yes
Carbonyl Iron	Micrometals	10	155 °C	45 MHz	Yes
PROGEN Co-Alloy	**PROGEN**	**Ultra-Low**	**>200 °C**	**>15 MHz**	**NO**

Key Technical Achievements

End-to-End Technological Know-How Established

The R&D lifecycle has successfully yielded a fully scalable, patent-pending technology suite ready for industrial implementation.

1. **Material Recipe:** Proprietary Co-based amorphous precursor chemistry.
2. **Phase Control:** Defined tension-annealing profiles for highly precise nanocrystallization.
3. **Manufacturing:** Automated, scalable core winding mechanics immune to compaction limits.
4. **Intellectual Property:** Complete technological know-how secured via patent filing (P2200466).

The physical limitations of high-frequency energy storage have been effectively redefined.

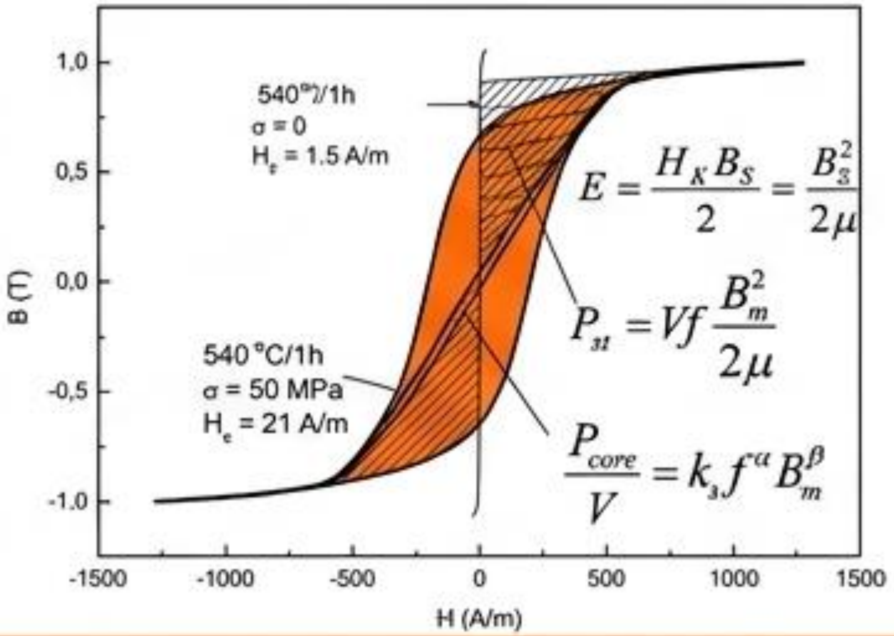
The Fundamental Engineering Challenge

The High-Frequency Requirement

Stored Energy: $E = \frac{B^2 V}{2\mu_0 \mu}$

Steinmetz Core Loss: $\frac{P_{core}}{V} = k_s f^{\alpha} B_m^{\beta}$

Insight: To maximize stored energy independently of DC bias currents up to saturation, ultra-low relative permeability (μ) is strictly required.

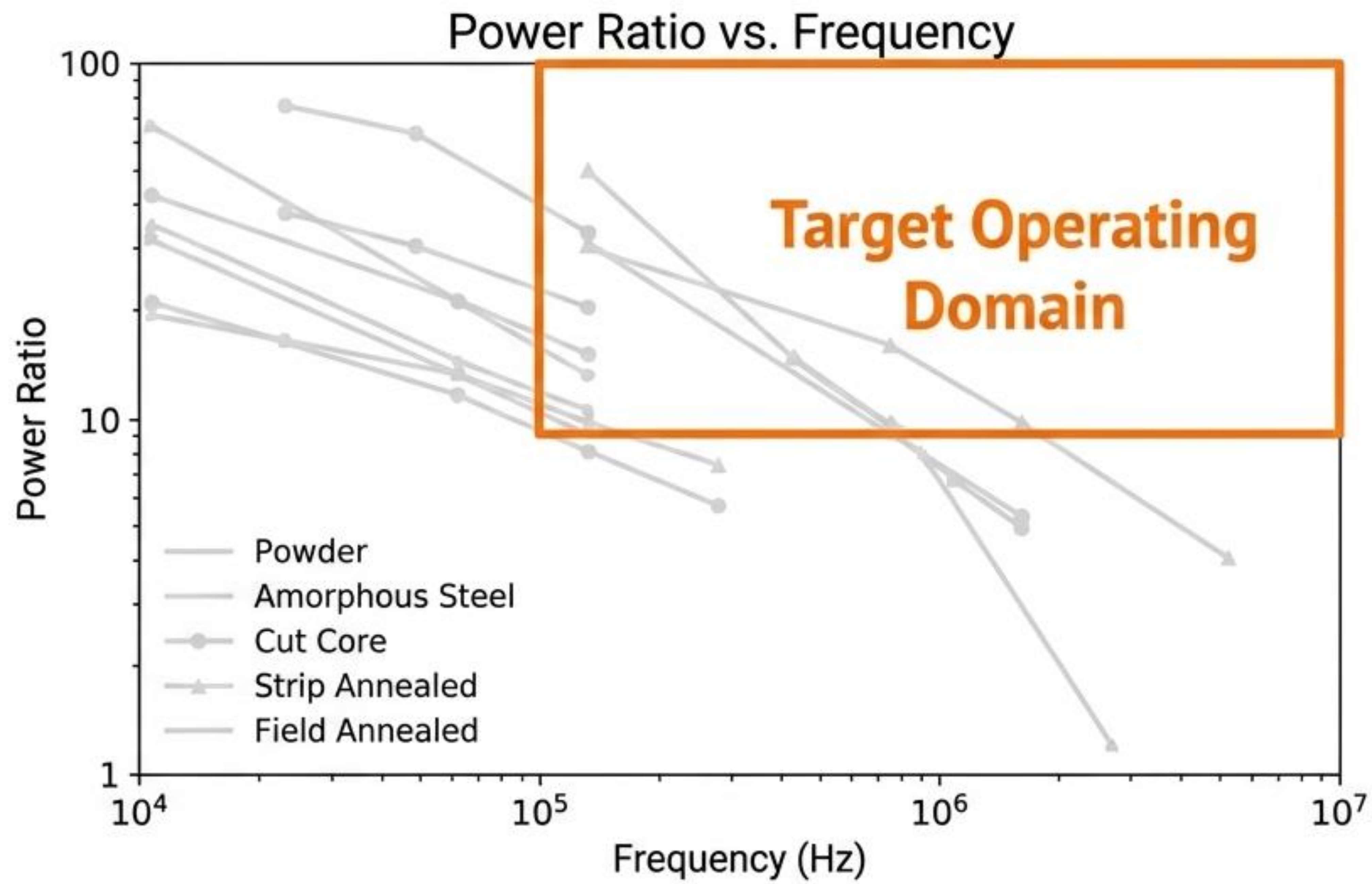


The Copper Loss Constraint

Copper Loss: $P_w = RI^2$

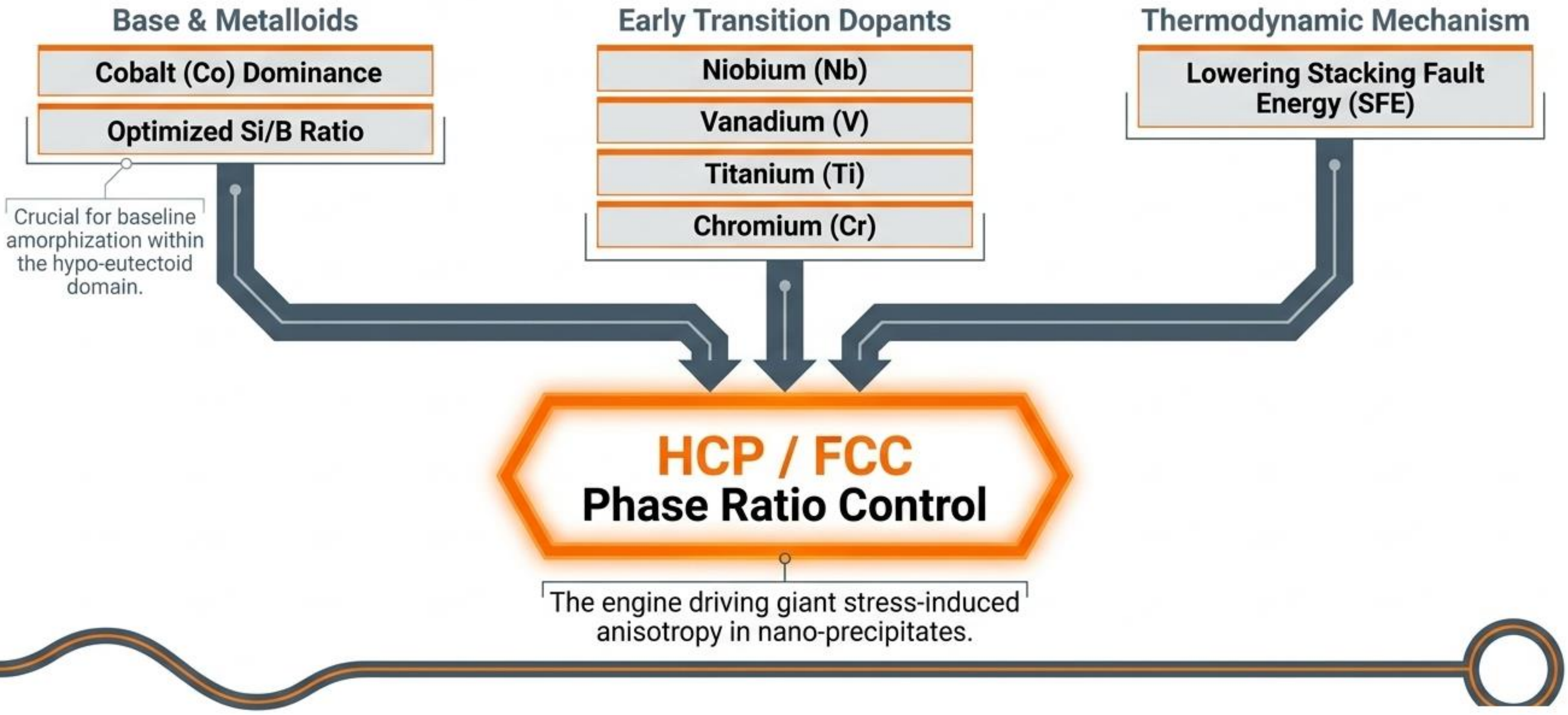
Insight: Dropping permeability too low necessitates higher winding turns, sharply increasing copper resistance and heat. Optimum must be precisely engineered.

The High-Frequency Performance Gap



Existing material families suffer rapid quality factor degradation above 100 kHz. Achieving superior performance ratios at >1 MHz requires a fundamental shift in alloy des in alloy des

Cobalt-Based Alloy Design Architecture



Synthesis Workflow: From Induction to Rapid Quenching

1. Induction Melting

Precise layering of alloy constituents to prevent disparate melting phases under vacuum/argon shielding.

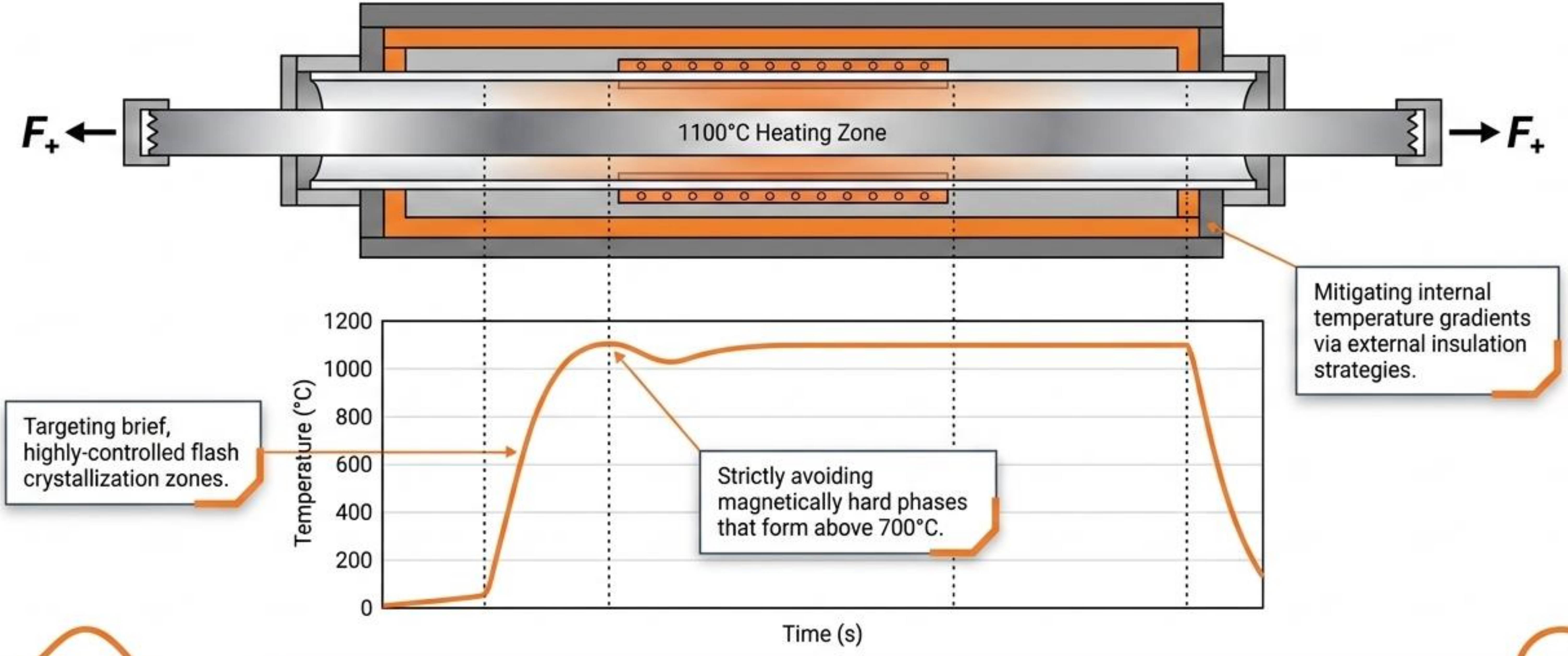
2. Homogenization

Achieving absolute melt homogeneity before casting.

3. Melt-Spinning

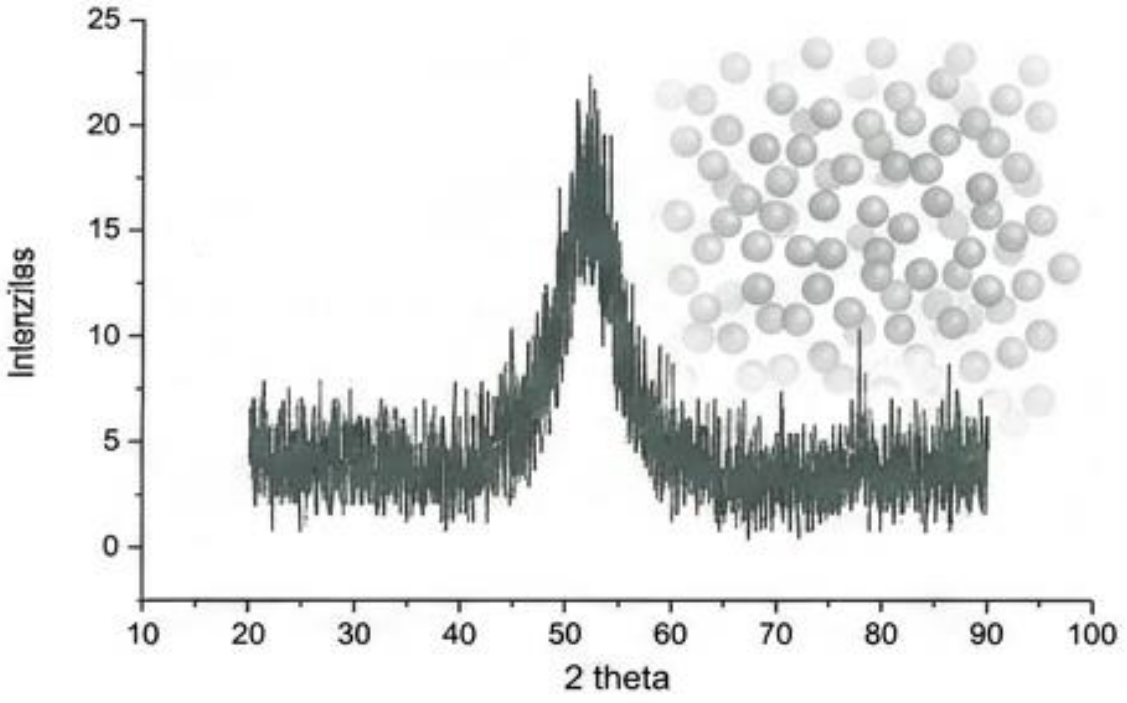
Ultrafast cooling onto a high-speed rotating copper wheel to freeze the atomic structure and bypass crystallization.

Continuous Stress-Annealing & Temperature Gradient Control



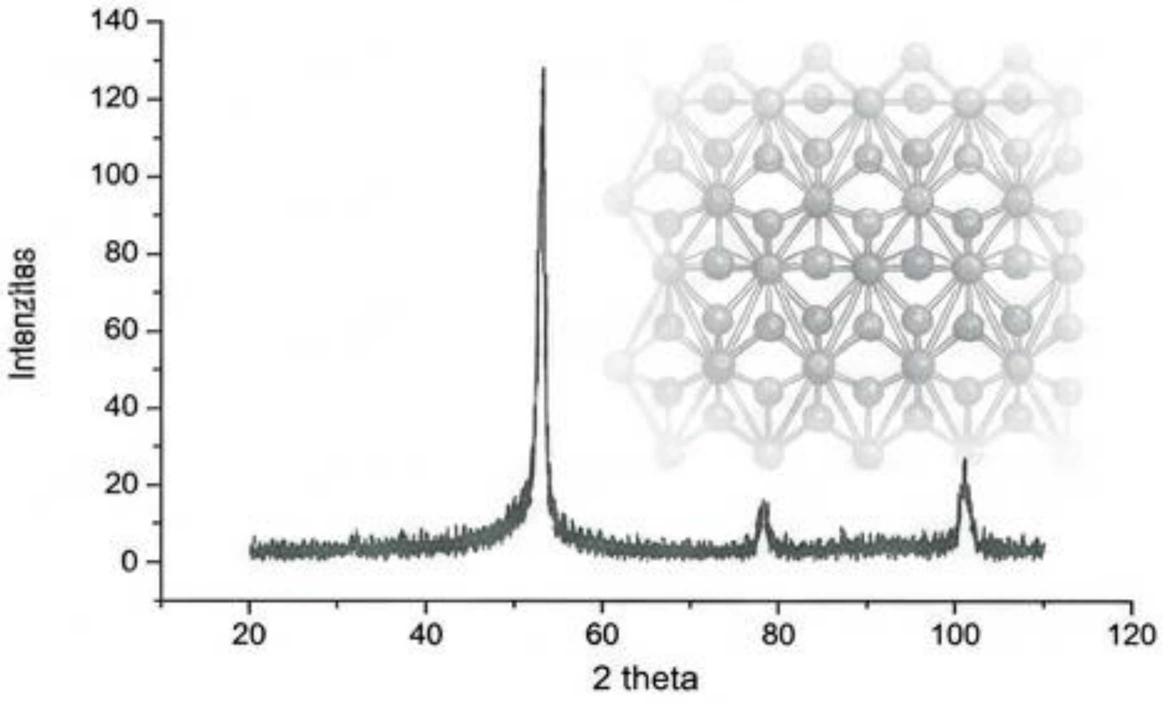
X-Ray Diffraction Validation of Phase Transformation

As-Cast State (Amorphous)



Broad intensity halo confirms the successful suppression of long-range atomic order during the melt-spinning process.

Annealed State (Nanocrystalline)



Sharp diffraction peaks confirm the highly controlled precipitation of nanoscale crystalline phases (HCP/FCC Co) embedded within the amorphous matrix.

Microstructural and Geometric Quality Control

QUALITY MATRIX

INGOT HOMOGENEITY VALIDATION

Evaluation of primary constituent mixing and internal crystalline macrostructure prior to casting.

RIBBON GEOMETRY THRESHOLD

Failed: Brittle Flakes

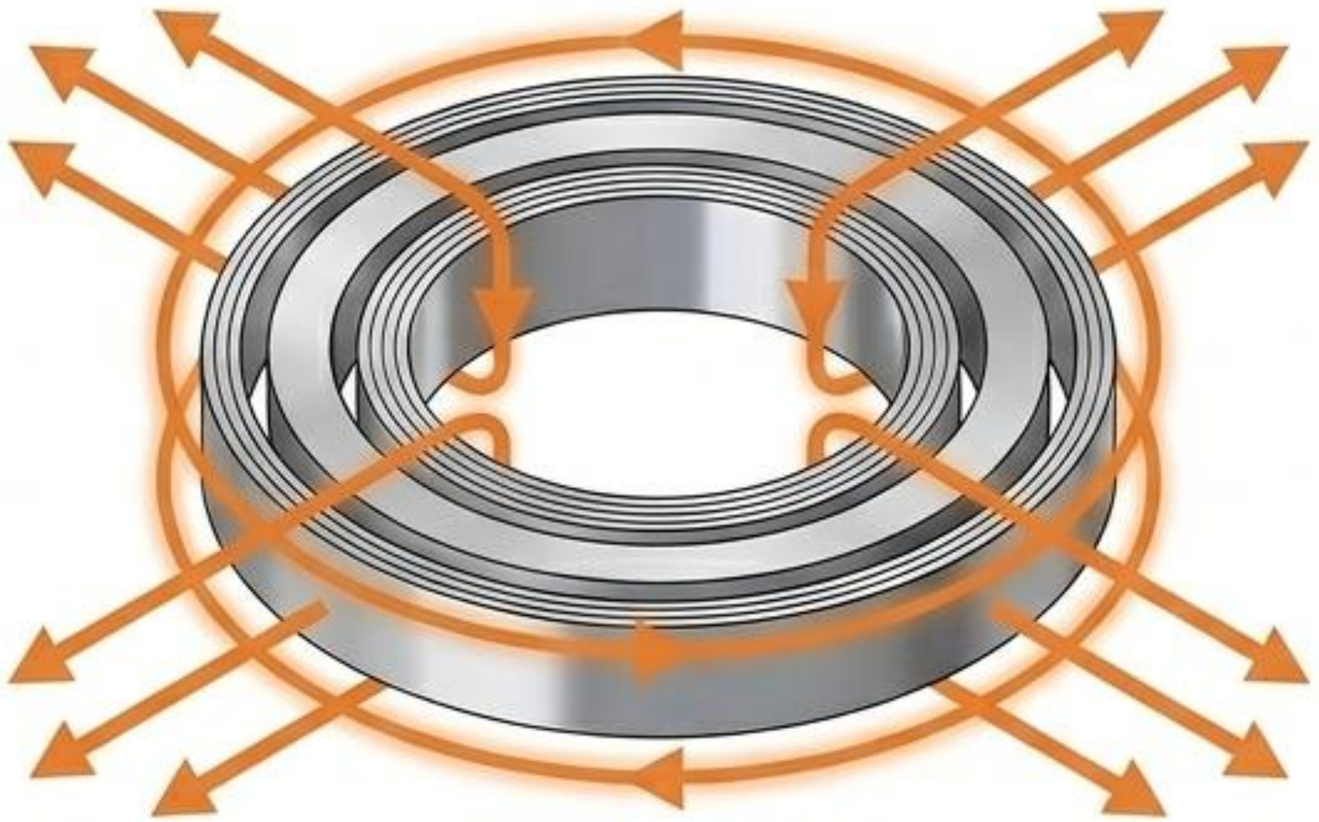
Failed: Discontinuous Filaments

Success: Flexible Continuous Ribbon

CRITICAL CONTROL PARAMETERS

- Cooling wheel speed
- Melt density & holding temperature
- Capillary gap distance
- Ejection angle

Magnetic Measurement & Anisotropy Induction



1. Early Transition Dopant Addition (V, Nb)

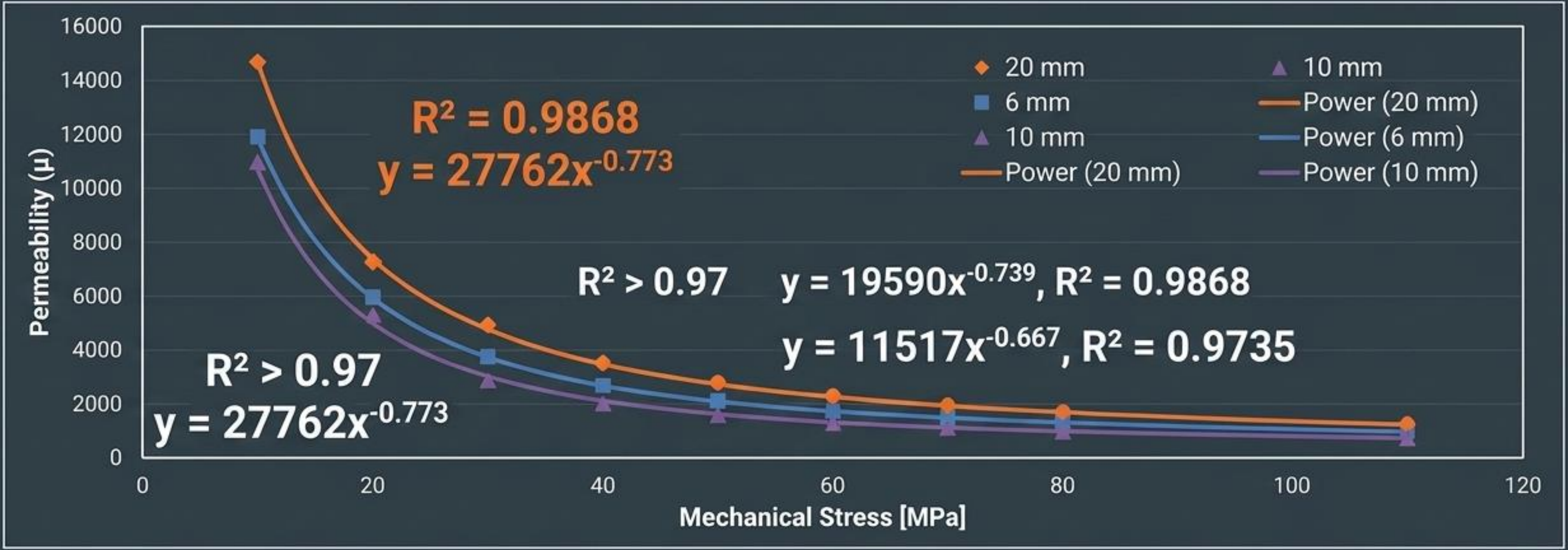
2. Heat Treatment Under Applied Stress

3. Deformation of FCC Phase
(High Packing Fault Density / HCP Domains)

4. Generation of Giant Stress-Induced Crystalline Anisotropy

CRITICAL INSIGHT:
The induced anisotropy energy (>70 kJ/m³ under 500 MPa) approaches the stored energy of bonded Nd-magnets, fundamentally locking in Virtual Bound States (VBS) and altering the magnetization curve.

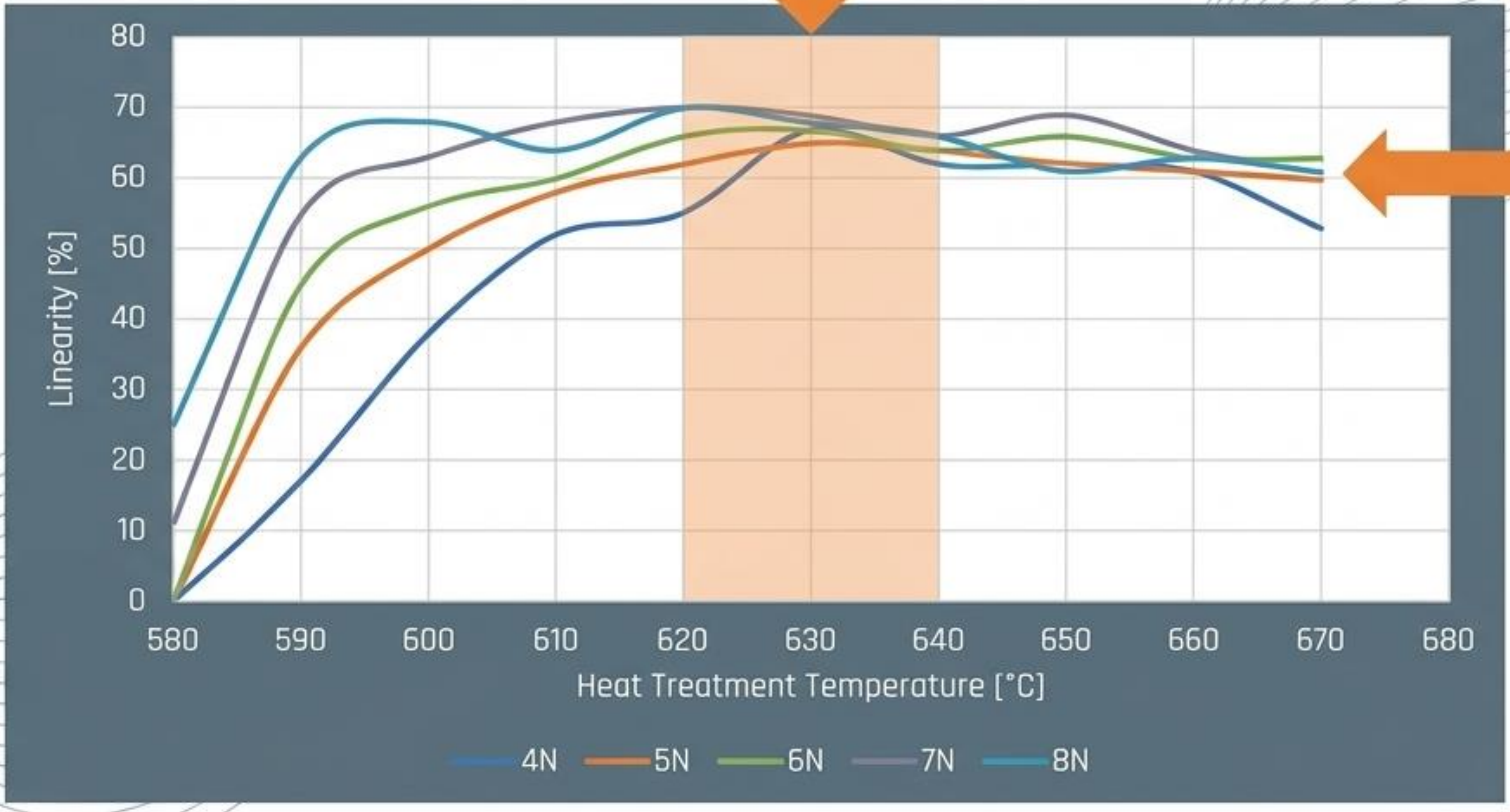
Mathematical Control of Permeability via Mechanical Stress



Permeability is not a fixed material constant; it is a precisely engineerable parameter mathematically dictated by applied tension during heat treatment.

High-Frequency Behavior: Linearity vs. Peak Temperature

Optimal Zone (~630°C):
Linearity peaks and permanently stabilizes.



Performance drop-off due to the irreversible precipitation of magnetically hard phases.

High operational linearity (>50% up to 2000 A/m) strictly guarantees independence from DC bias curpm DC bias curr

State-of-the-Art Benchmark Analysis

Material Technology	Max Temp Limit	Max Frequency Limit	Linearity Profile	EMI/RFI Hazard
MPP Powder Core	200°C	2 MHz	Low	High (Air Gap)
High Flux	200°C	1 MHz	Medium	High (Air Gap)
Kool Mu	200°C	900 kHz	Low	High (Air Gap)
Fair-Rite 67	110°C	20 MHz	Low	None
Carbonyl Iron	155°C	45 MHz	Low	High
Co-Based Nanocomposite	**200°C**	**2 MHz**	**Extreme**	**Zero (Closed Toroid)**

Unlike powder cores, the closed continuous toroidal structure inherently eliminates localized fringing flux and severe EMI/RFI radiation problems while maintaining elite frequency and thermal limits.

Process Optimization for Industrial Scaling

Melt Temperature (ΔT_m - T_g)

Crucial for defining dynamic viscosity and guaranteeing glass-forming ability before casting.

Cooling Wheel Velocity

Strictly dictates ribbon thickness and the absolute lock-in of the amorphous atomic state.

Capillary-to-Wheel Gap

Geometrically controls the initial liquid melt puddle shape and ejection angle.

Holding Time

Precisely limits initial crystalline nuclei formation in the melt prior to expulsion.

Optimization via Design of Experiments (DOE) yields reproducible, continuous ribbon geometry, ensuring commercial manufacturability and eliminating brittle flaking.

The Materials Innovation Pipeline: Synthesis Summary

Composition

Mastery of early early transition dopants to force Stacking Fault Energy (SFE) reduction.

Process

High-yield, rapid-quench amorphization of Co-rich alloys into purely continuous metallic ribbons.

Treatment

Precise induction of giant stress-anisotropy via controlled mechanical tension and flash-crystallization.

Ultra-Low Permeability Nanocrystalline Toroids

Engineered to permanently replace discrete powder cores in next-generation high-frequency topologies.

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NATIONAL RESEARCH, DEVELOPMENT AND INNOVATION OFFICE
HUNGARY

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THANK YOU
FOR YOUR ATTENTION!