Electromagnetic properties of austenitic stainless steels in cryogenic, high magnetic field environments

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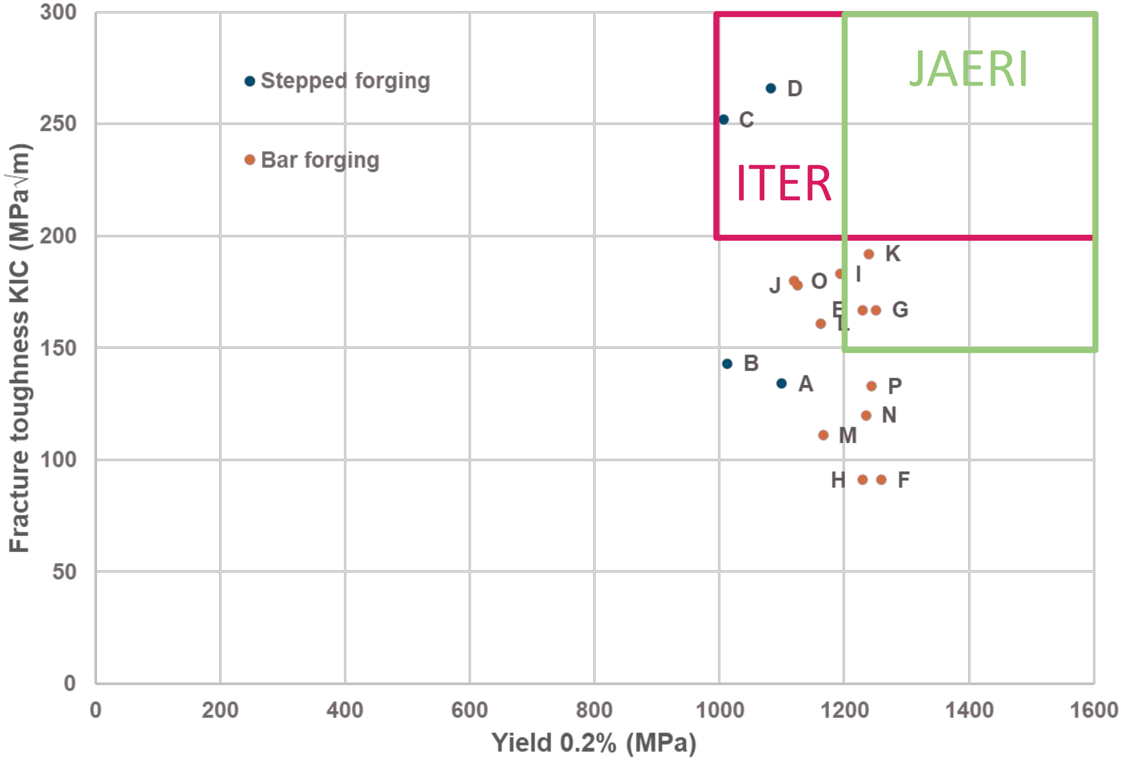
Compact tokamak SPARC will be ~80% austenitic stainless steel by mass for its cryogenic strength and toughness



** Data collected by CryoMak Lab at KIT

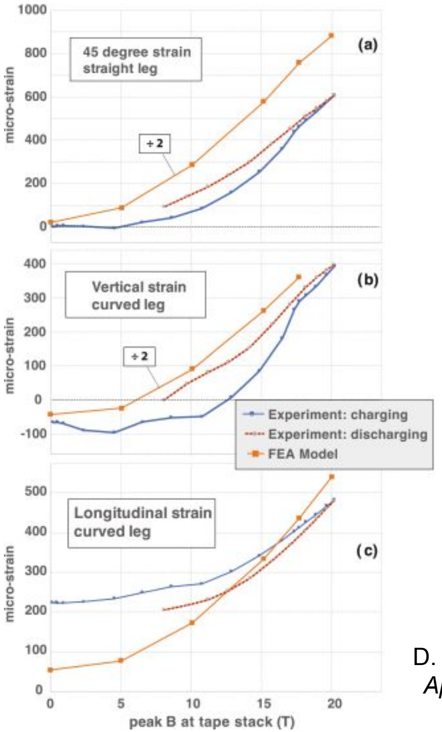
Mechanical properties of many austenitic stainless steels tested at 4 Kelvin showed variable results outside of previous magnet structural design windows

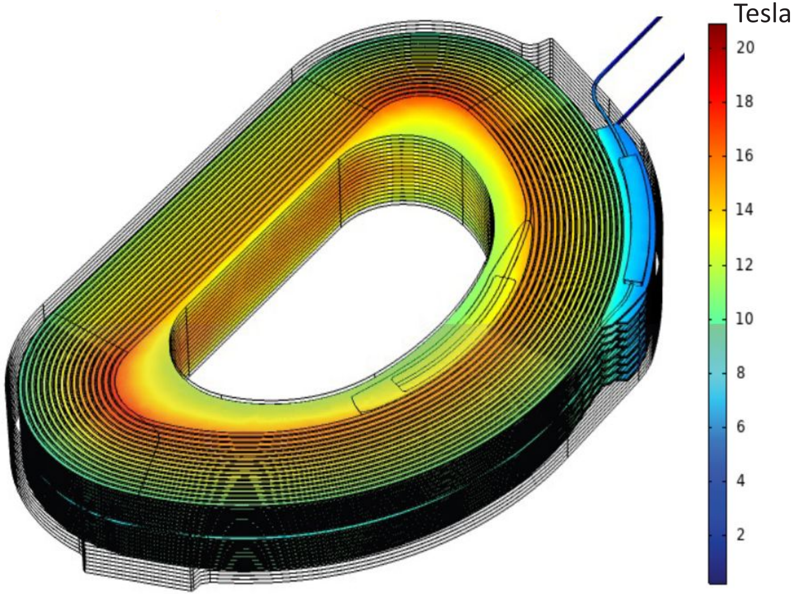
Electromagnetic properties of ferrous alloys impact tokamak design and operation

Lorentz forces drive mechanical design

Magnetization and hysteresis determine operating windows and magnet controls

Resistivity governs failure modes during quench





D. G. Whyte et al., *IEEE Trans. on Applied Superconductivity*, 2024

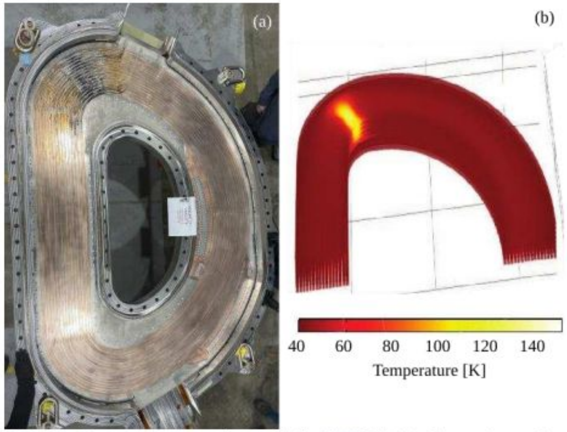
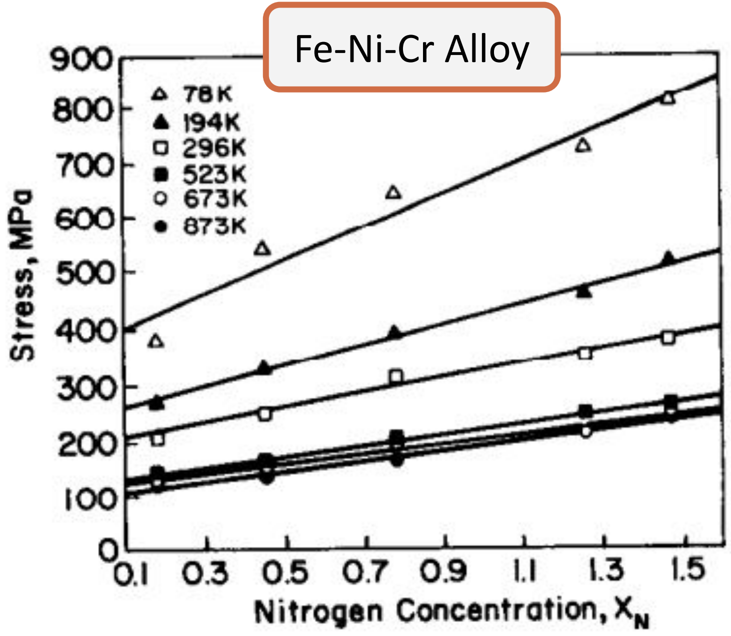


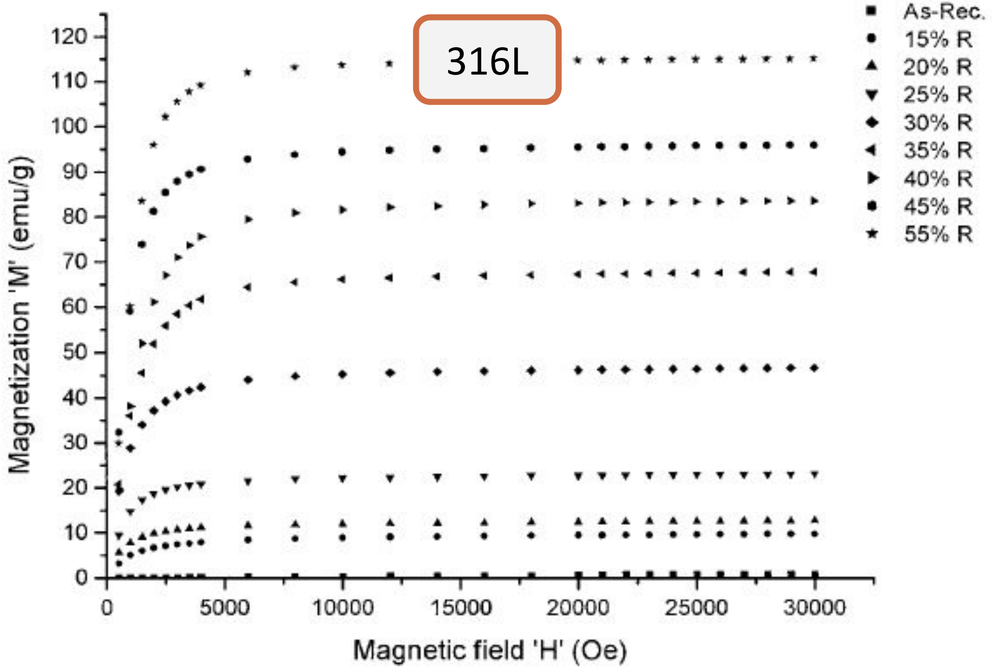
Fig. 8: Post-quench analysis of the TFMC. (a) shows Pancake #12 during the post-mortem with a sharply defined region of thermal damage in the upper-left tight corner. (b) shows a 3D FEA simulation 170 s into the evolution of a 30 kA quench; the burn region is reproduced almost perfectly.

Z. S. Hartwig et al., *IEEE Trans. on Applied Superconductivity*, 2024

Cryogenic strengthening mechanisms relate to magnetic performance



M. L. G. Byrnes et al., *Acta Metallurgica*, 1987



Mumtaz, K. et al., *Jrnl. of Mat. Sci.*, 2004

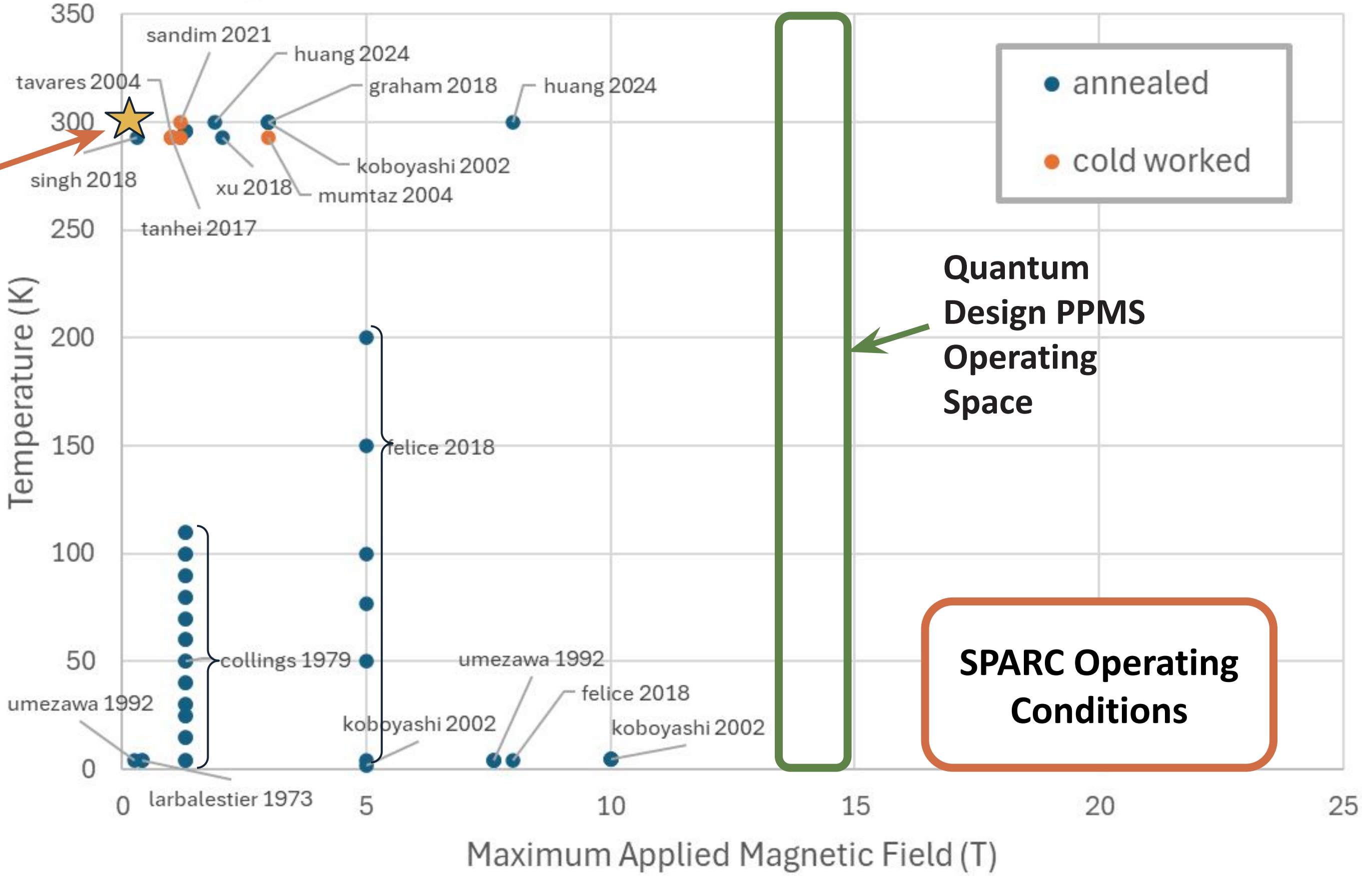
⇧ Nitrogen ⇧ Strength ⇩ Magnetization

⇧ Dislocations ⇧ Strength ⇧ Magnetization

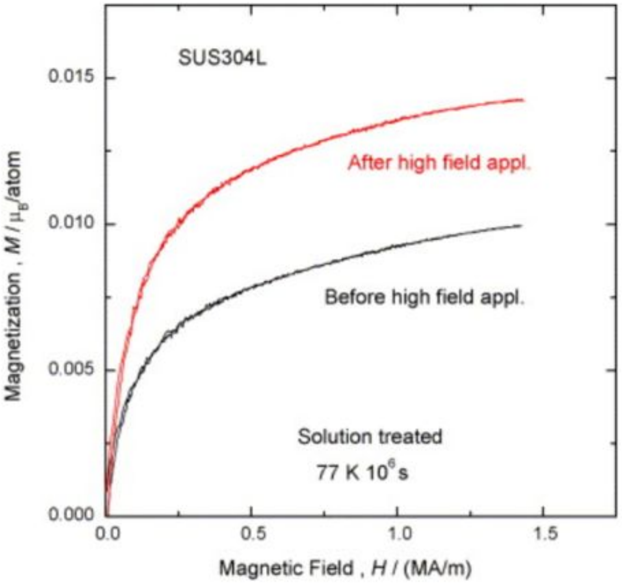
A gap in literature exists on electromagnetic properties for cryogenic temperatures, cold worked material, and high magnetic fields

Industry standard magnetic permeability probe measurements per ASTM A342

Magnetization measurements of austenitic stainless steels



SPARC magnet acceptance testing allows us to expose material to cryogenic temperatures, stress, and high field simultaneously



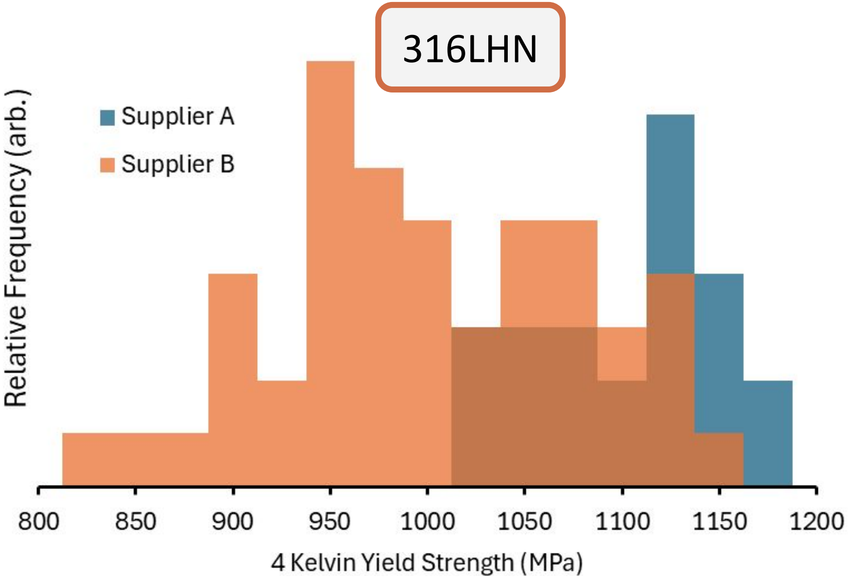
T. Fukuda et al., *Mat. Sci. and Eng.: A*, 2006

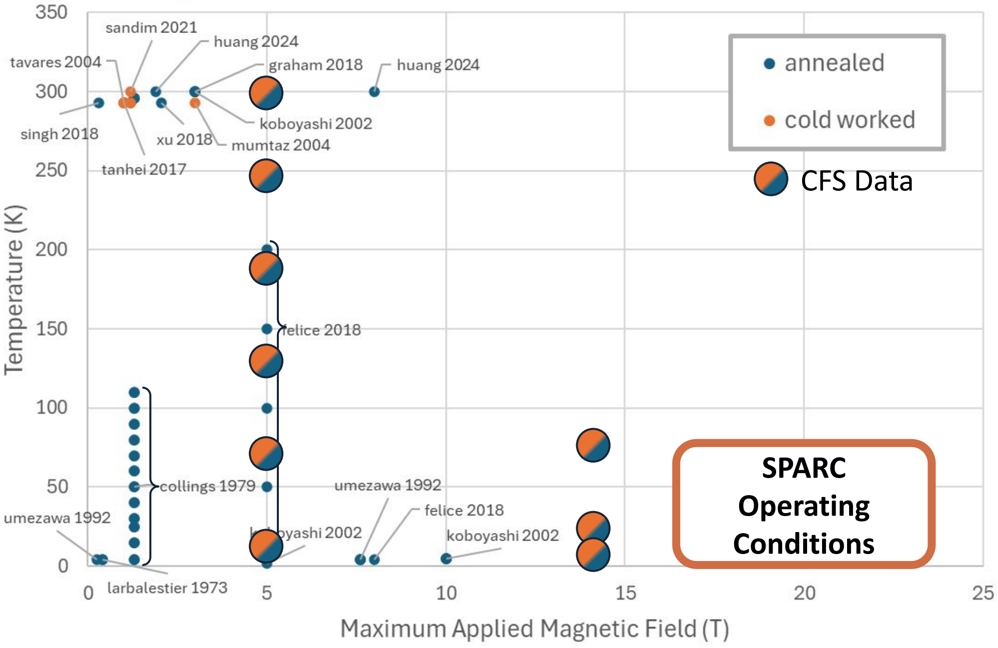
Expected test environment:

- 20 K
- 20 T
- 150 Mpa

Measurements done at cryogenic temperatures after exposure

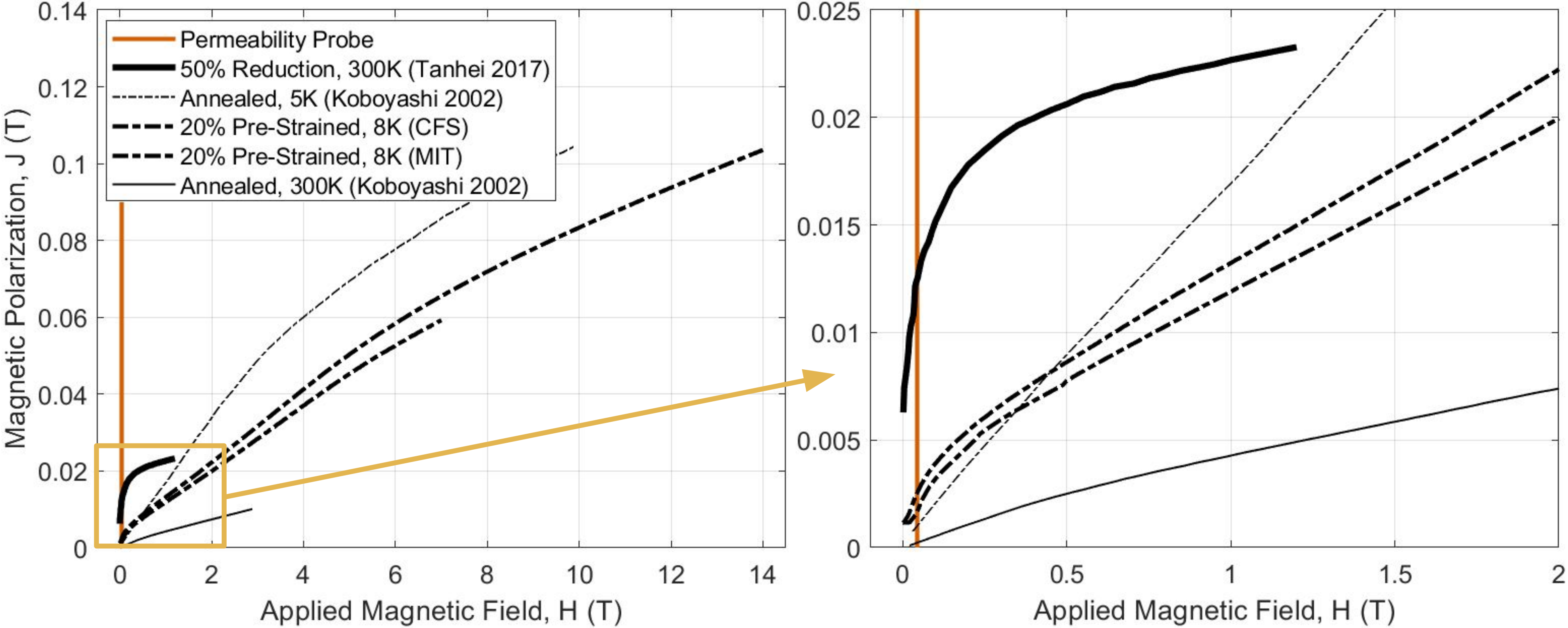
CFS is compiling a database of magnetization measurements on many materials using in-house and collaborator-done measurements





Single measurements are not enough to show the distribution of a property from one material

Cold worked magnetization not easily extrapolated from room temperature measurements



All 316L

Proposed model uses room temperature low field measurements to estimate cryogenic, high field behavior

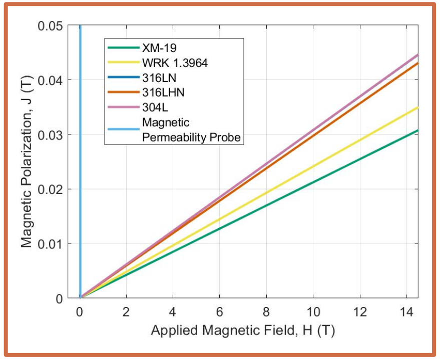
Ferrite number measurement → Volume % δ → **Initial permeability and low field behavior**

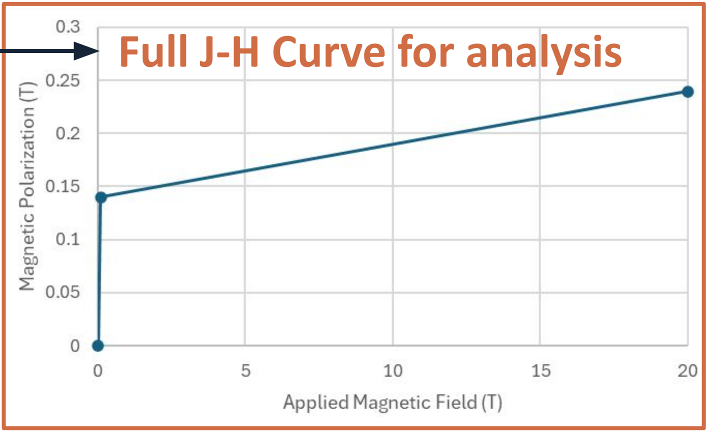
e.g. FN = 10

Volume % Ferrite ≈ 0.7 * FN = 7 vol% ferrite

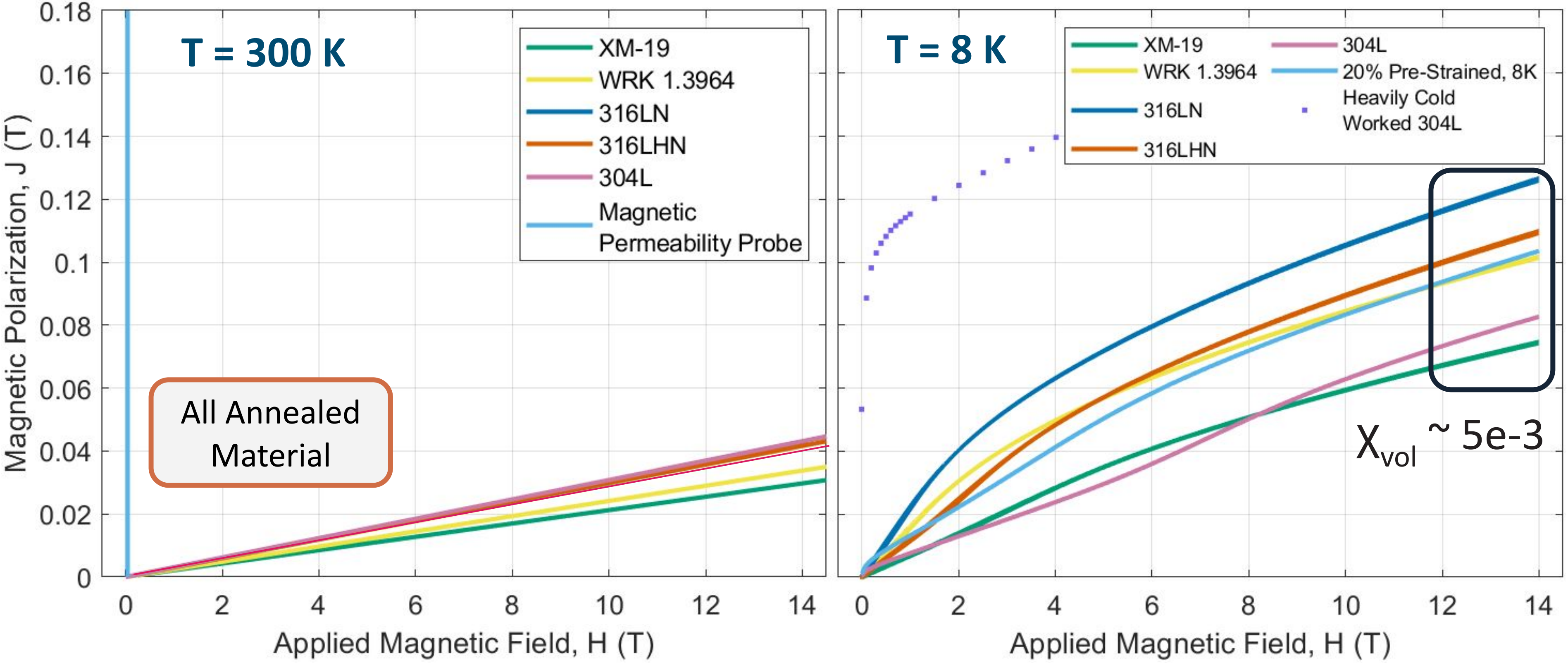
J_saturation ~ 2 T
J_sat of weld ~ 2*0.07 = 0.14 T

Base material paramagnetic component → **High field behavior** → **Full J-H Curve for analysis**

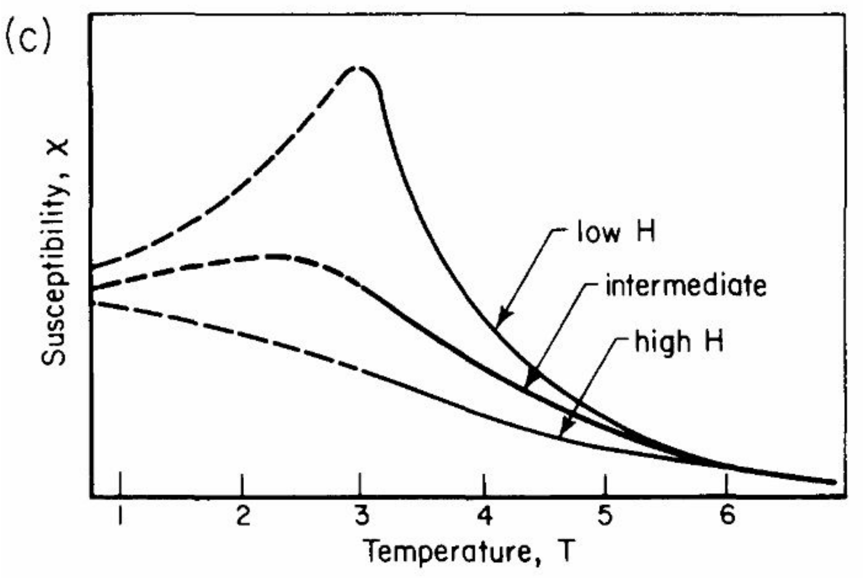




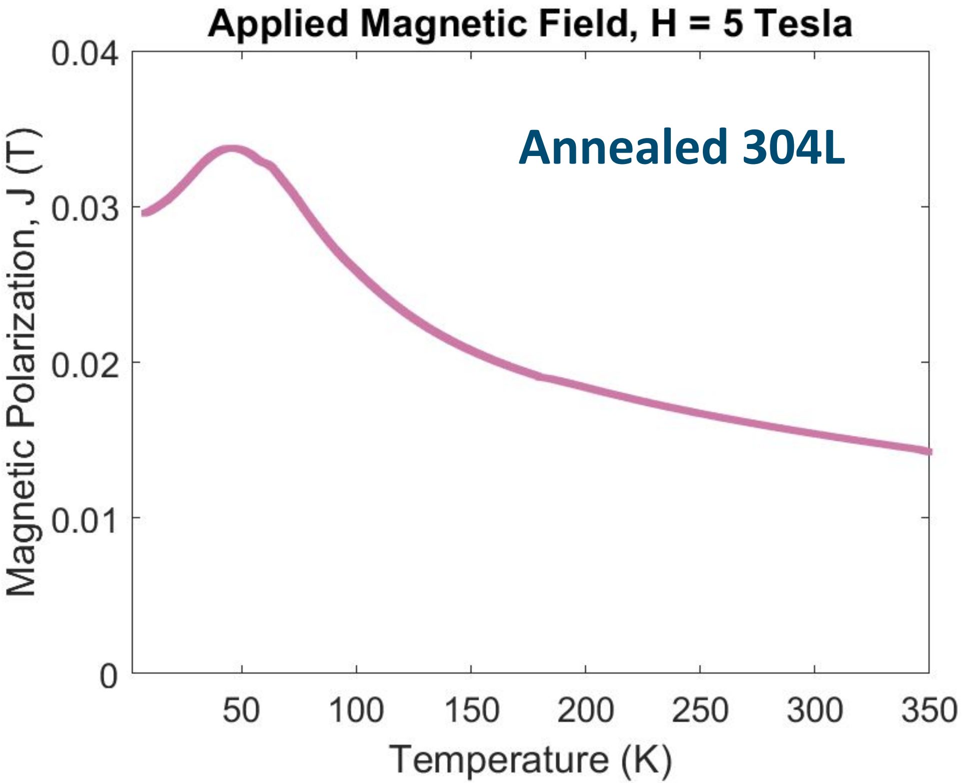
Austenitic stainless steels exhibit large paramagnetic moments and anomalous behavior ~5 T at cryogenic temperatures



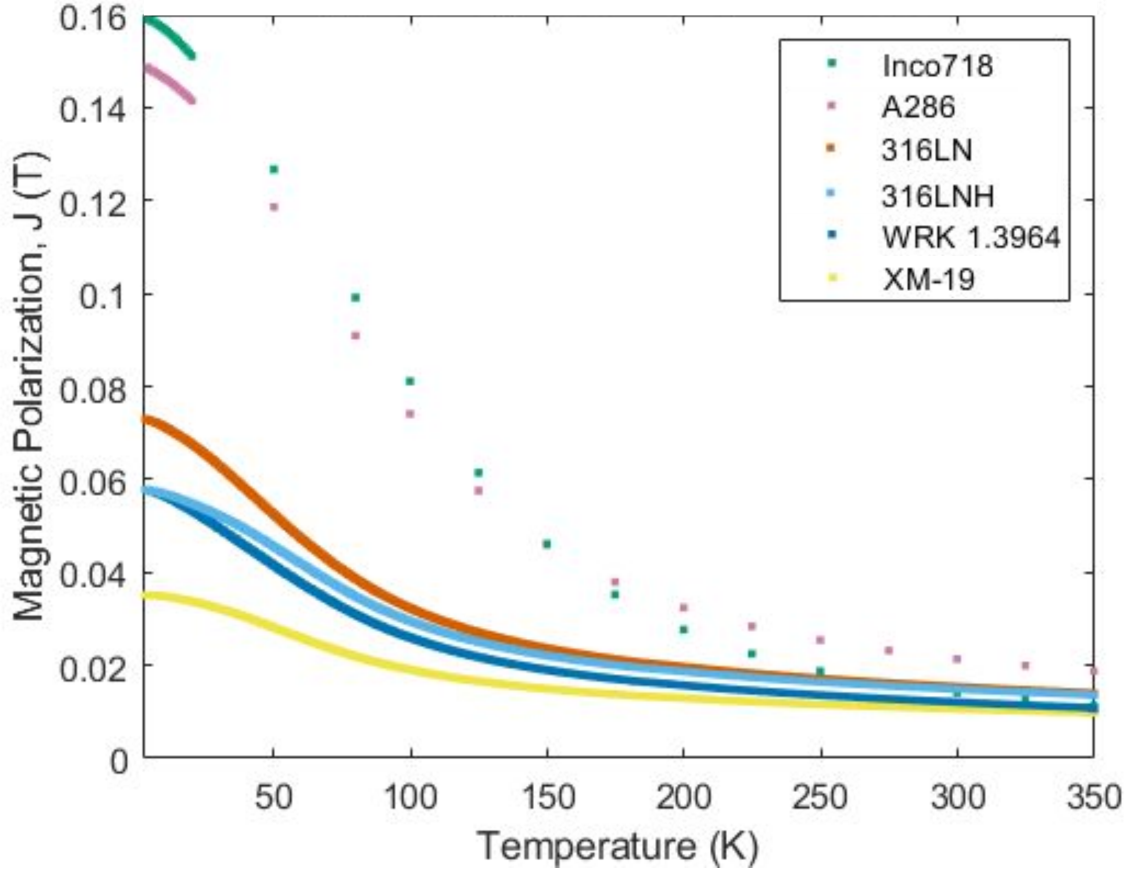
No consensus exists on fundamental mechanisms for 316 and 304 anomalous behavior



E. W. Collings et al., *Cryogenics*, 1979



Other superalloys that are paramagnetic at room temperature exhibit ferromagnetism at low temperatures



Spin glass transition?

Magnetic nano precipitates?

SPARC is pushing materials physics limits and EM property data helps make the device a reality

- Tokamaks are designed to make a precise magnetic field
  - Magnetization and hysteresis of component materials impacts this
- Literature is lacking in combined environment measurements
  - Room temperature measurements cannot be extrapolated well
  - CFS is building out a database of high field, low temperature measurements as well as in-situ SPARC magnet condition measurements
- A volumetric approach is proposed to estimate magnetization curves when only room temperature measurements exist

Future work we hope to see

- Fundamental mechanisms to understand limits of materials
- Non-destructive evaluation tools for high field magnetization
- Non-sample dependent reporting of magnetic properties
- Predictive models
  - Temperature dependent ones for translating an industry standard magnetic permeability test to high field, cryogenic behaviors
  - Chemistry dependent ones for helping guide alloy design
- Exploring other properties:
  - Electrical resistivity
  - Magnetoresistance
  - Magnetostriction

Acknowledgements

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- Charles Settens @ MIT.nano
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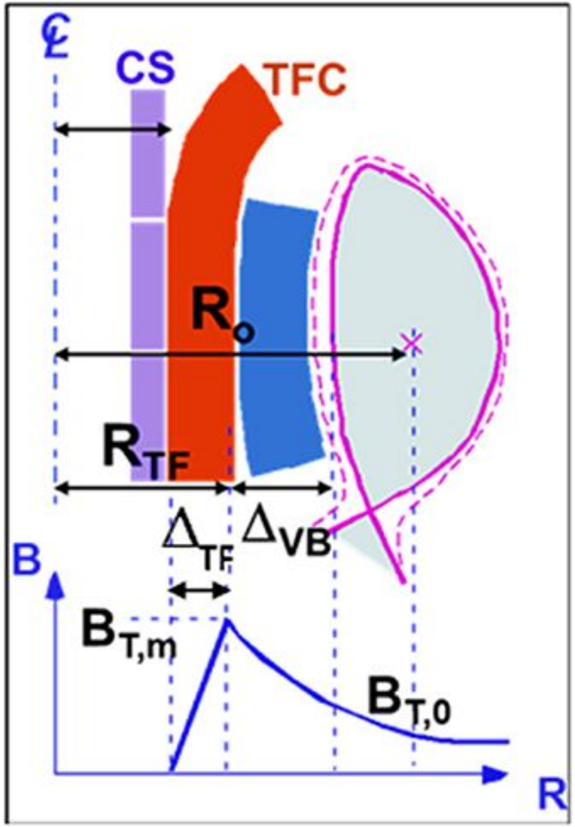
Supplementary

Tokamak magnet structural design driven by magnetic field requirement



G. Federici et al, *Nucl. Fusion*, 2024

Magnetic hysteresis impacted PF coil charging on KSTAR tokamak

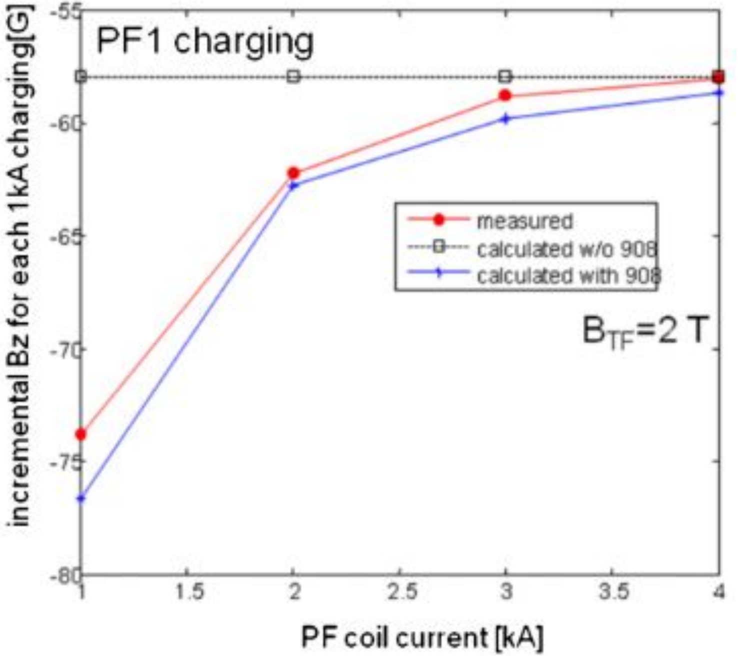


Fig. 3. Comparison between the measurements by the HS located at the $R = 1.8$-m midplane and the calculations at $R = 2.02$ m. The field generated per 1 kA of PF1 charging is shown for different levels of PF1 charging. It is clearly shown that the magnetization in the PF1 coils is saturated at $I_{PF} = 4$ kA, $B_{TF} = 2$ T. Each PF1 coil has 180 turns.

Yoon, S. W. et al., *Fusion Science and Technology*, 2014