Fermilab

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Magnetic Materials for Pulsed Power

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Outline

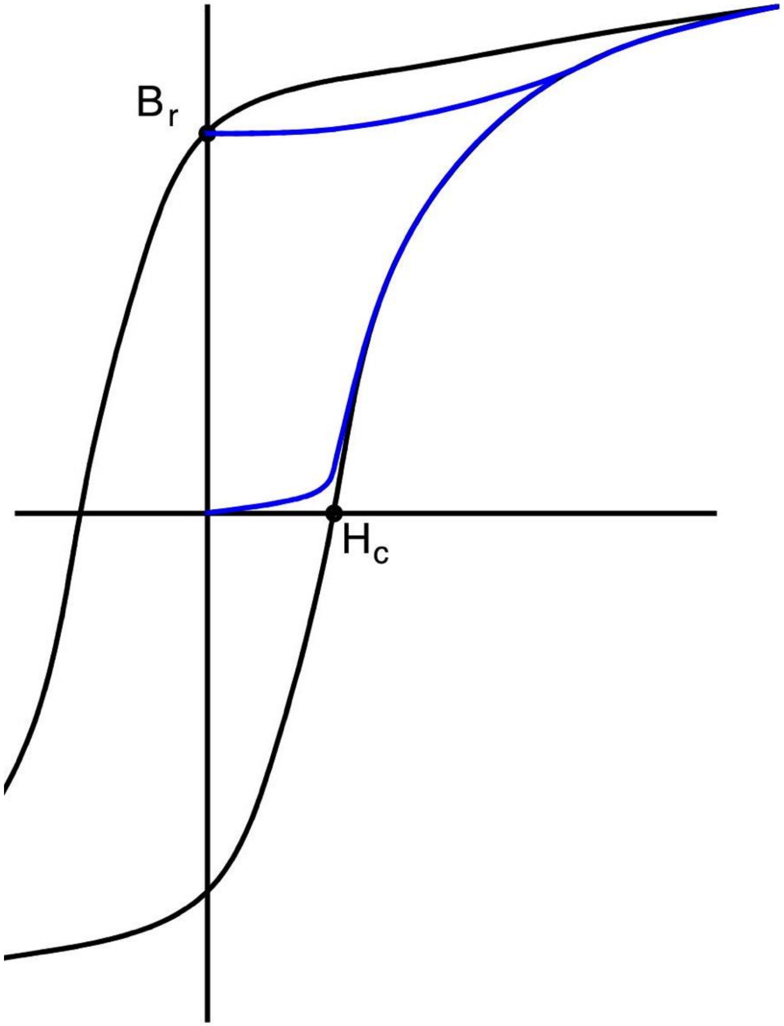
- Magnetic Properties Overview
  - permeability, saturation, losses
  - B-H loop and initial conditions
- Ferrite Specific
  - Ferrite production
  - Pulse measurement
- Examples
  - Considerations in choosing material
  - Kicker magnet
  - Kicker saturating ferrite
  - Recent procurement experience

Magnetic Properties

- Types of materials (typical, various parameters for all types)
  - Nickel Zinc Ferrite
    - B_{sat} ~ 0.3 T, f_{corner} ~ 1 MHz, $\mu_{r,initial}$ ~ 1 k, ρ ~ $10^5 – 10^8$ Ohm cm
  - Manganese Zinc Ferrite
    - B_{sat} ~ 0.4 T, f_{corner} ~ 100 kHz, $\mu_{r,initial}$ ~5 k, losses ~ 0.5 W / cm^3, ρ ~ $10^1 – 10^3$ Ohm cm
  - Finemet tape wound steel (specialty alloy, special processing)
    - B_{sat} ~ 1.2 T, f_{corner} ~ 10 kHz, $\mu_{r,initial}$ ~30 k, losses ~ 0.3 W / cm^3
  - Tape wound 3% silicon steel (not special alloy, 250 µm thick)
    - B_{sat} ~ 1.9 T, f_{corner} ~ 1 kHz, $\mu_{r,initial}$ ~2 k, losses ~ 8 W / cm^3
- B_{sat} and $\mu_{r,initial}$ at 1 kHz, losses at 100 kHz, B ~ 0.2 T, f_{corner} where real part of small signal μ_r starts to reduce, not maximum use

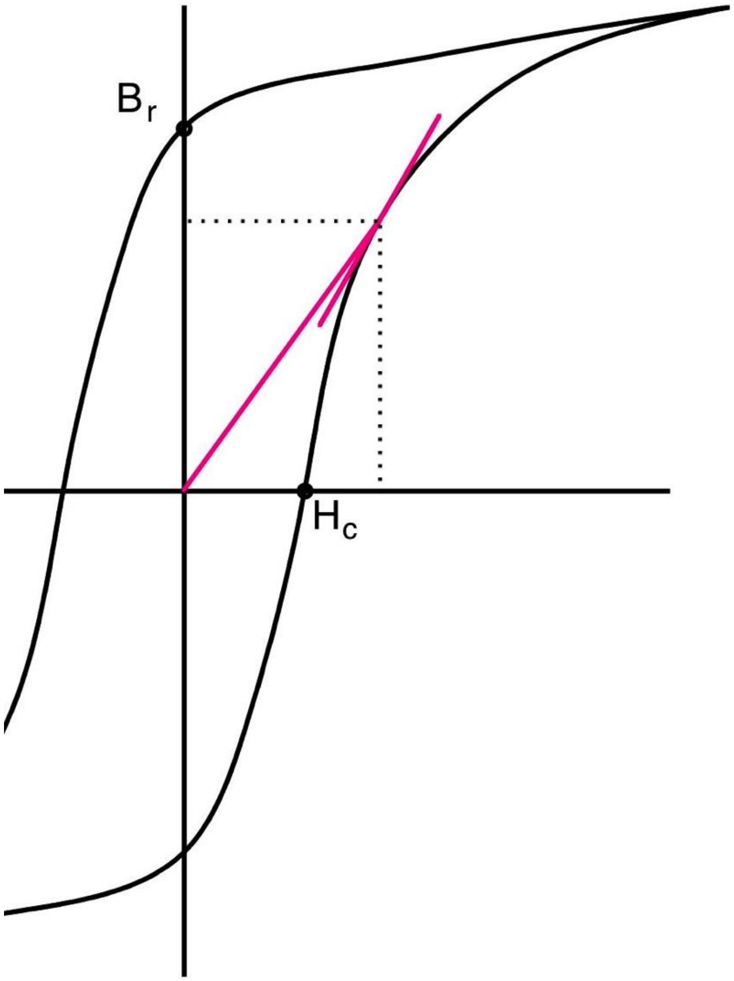
Magnetic Properties

- Constituent Equations
  - $B = \mu_0 H + M(H)$
  - $B = \mu H = \mu_r \mu_0 H$
  - No hysteresis
  - No time dependence
- Br dependent on drive level
- Hc dependent on drive frequency
- No negative drive applied, then remain at Br until next cycle, minor loop excursion
- Area between curves has units of $T / m^2 * A / m =$ Joules/m^3 , loss per cycle



Magnetic Properties

- How to define permeability?
  - Pulse / Amplitude permeability
    - Chord from 0,0
  - Incremental permeability
    - Slope at point
  - Pulse power generally can't consider simple, constant permeability if no or very small air gap
- The amplitude of the excitation, the frequency and the applied waveform all effect the shape of the measured loop



Magnetic Properties

- Equations relating circuits (loops) to geometry and fields
  - Maxwell's laws
  - Integral [E • d*l*] = -d / dt Integral [B • dS]
    - Assuming uniform E, B and non changing path / surface
      - $V = -dB/dt\ A_{surface}\ N_{turns}$
  - Integral [B • d*l*] = μ_0 Integral [J • dS] + $1/c^2$ d / dt [E • dS]
    - Assuming path not in magnetic material, uniform B, J, non changing path / surface and dE/dt small
      - $H\ l_{path} = J\ A_{surface}\ N_{turns} = N_{turns}\ I$
    - The last assumption of small dE/dt may be poor in fast pulsed systems
      - Displacement currents may be appreciable
- Circuit and field simulation makes many assumptions
  - Understand what you are modeling and try to make predictions that you can check

Magnetic Materials / Other Properties

- Dielectric Strength
  - NiZn ferrite materials have higher dielectric strength than MnZn
  - Tape wound material, need to know insulation strength for induced voltage per lamination
    - Finemet, need to make sure have appropriate insulation
    - Specialty steel may need impregnation
- Relative Dielectric Constant / Resistivity
  - NiZn typical range $\varepsilon_r \sim 10\text{-}100$, $\rho \sim 10^8 - 10^5$ Ohm cm
  - MnZn typical range $\varepsilon_r \sim 10^2\text{-}10^4$, $\rho \sim 10^3 - 10^1$ Ohm cm
  - Tape wound steels are conductive along the tape
- Magnetostriction (and inverse)
  - Relationship between magnetic parameters and displacement
  - A problem with some steel alloys and sometime MnZn

Ferrite Production

- Control of raw materials important
  - Ferrite is iron oxide with various amount of other oxides
  - Mn, Ni and Zn are most common
    - These replace some of Fe in the lattice
  - Mix variations and impurities change ferrite properties
- Raw materials are formed into small granules
  - 2 processes, wet vs dry, different approach, similar end result
- Form into rough shape and compress
  - Small toroids (~ 30 mm) generally formed by die stamping
  - Press blocks using high pressure (100s atmospheres)
  - Or very high pressure, isostatic (1000 atmospheres)

Ferrite Production

Effect of composition and temperature on saturation flux density [1]

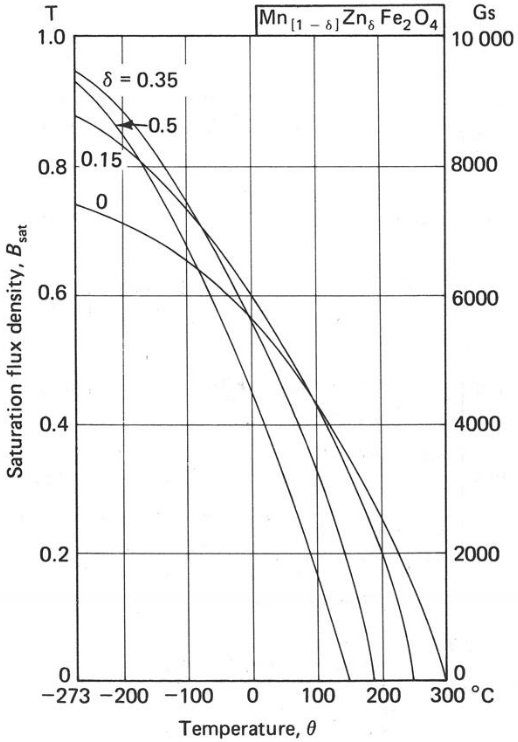


Figure 3.3.1

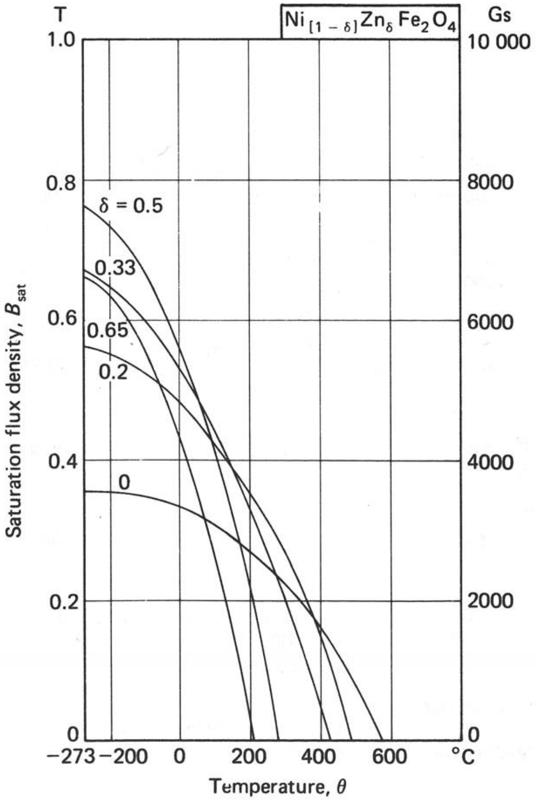


Figure 3.3.2

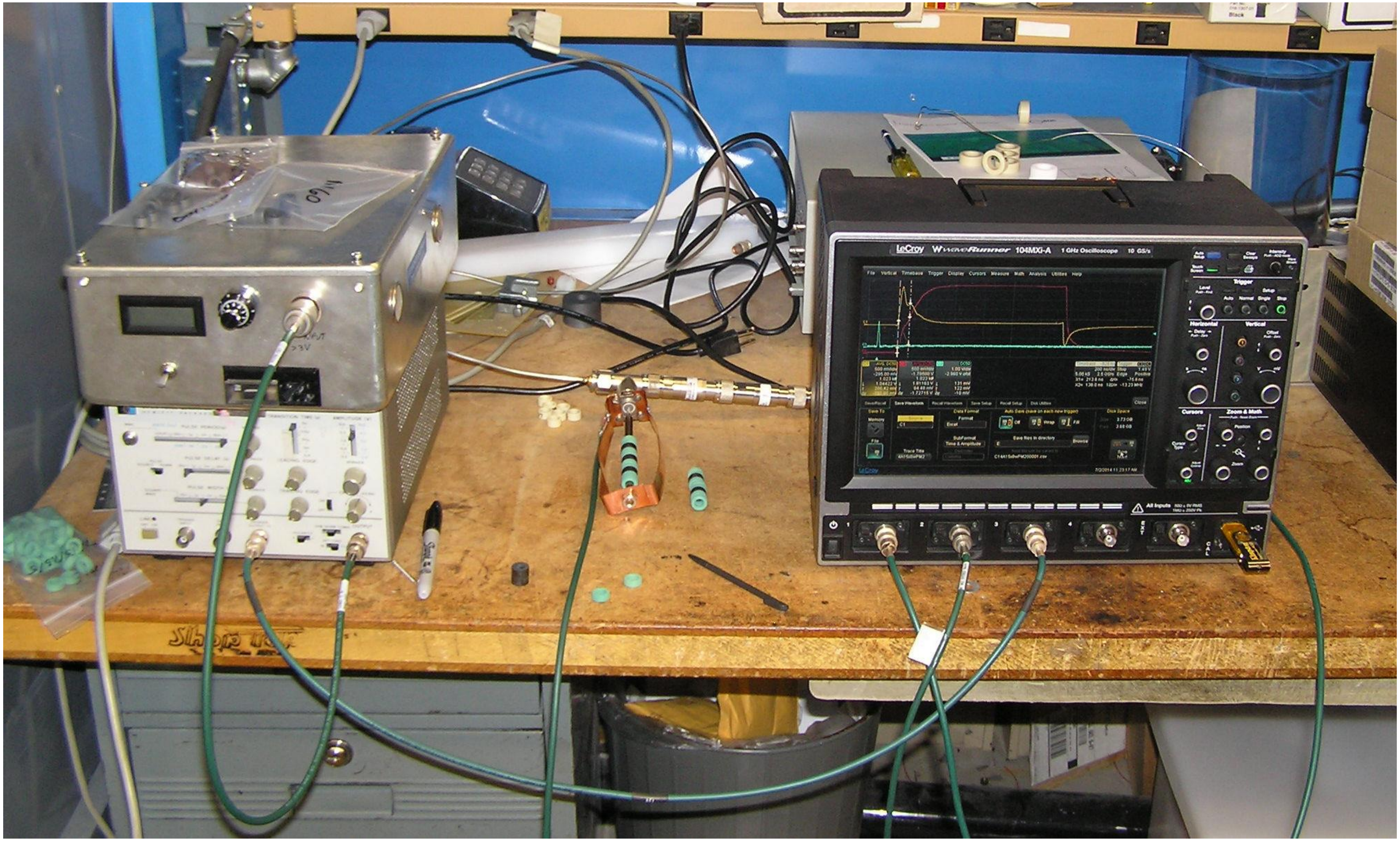
Ferrite Production

- Sintering
  - Controlled heating with controlled atmosphere to temperature on order of 1000 C
  - Shrinkage on order of 10-20%, controlled within +/- few %
- Final Finishing
  - Grinding surfaces flat
  - Some specialty ferrites have shapes which require special tooling and machining
    - If special vacuum requirements are needed, this is the step where problems can occur; grinding solution must be water based
- Gluing / Cementing
  - Epoxy resins for joining ferrites, usually large air gap someplace
    - Fermilab specifies use temp of > 150 C for radiation resistance

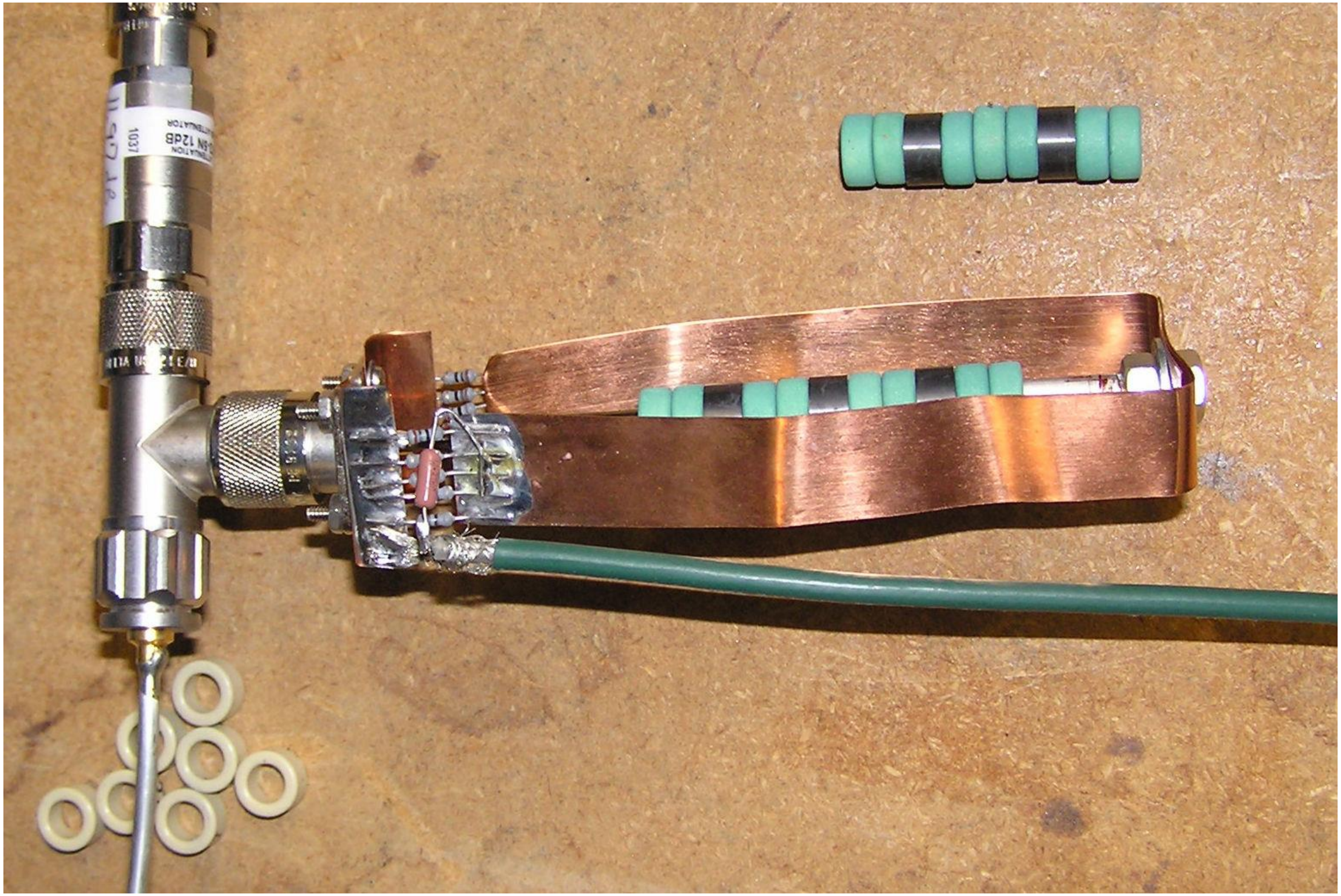
Material Measurements

- The test waveform shape and rise time should be similar to application
  - 1 kHz sine wave measurements will give a B H loop which may not be useful for 1 µs pulse without reset field
- The shape of the core should have similar size and shape to final
  - Fabrication methods for small toroid samples are not the same as large blocks, use large toroid
  - Toroids can be easier to analyze; make sure you understand where the highest fields are in an E-I or pot core
- Sample test setup for high speed saturation application
  - Actual size cores, small toroids
  - Applied voltage was ~100 V, ~20 ns rise time with 50 Ohm source, but real voltage is ~30 kV, ~20 ns rise time
  - Not the same waveform amplitude, hard to scale

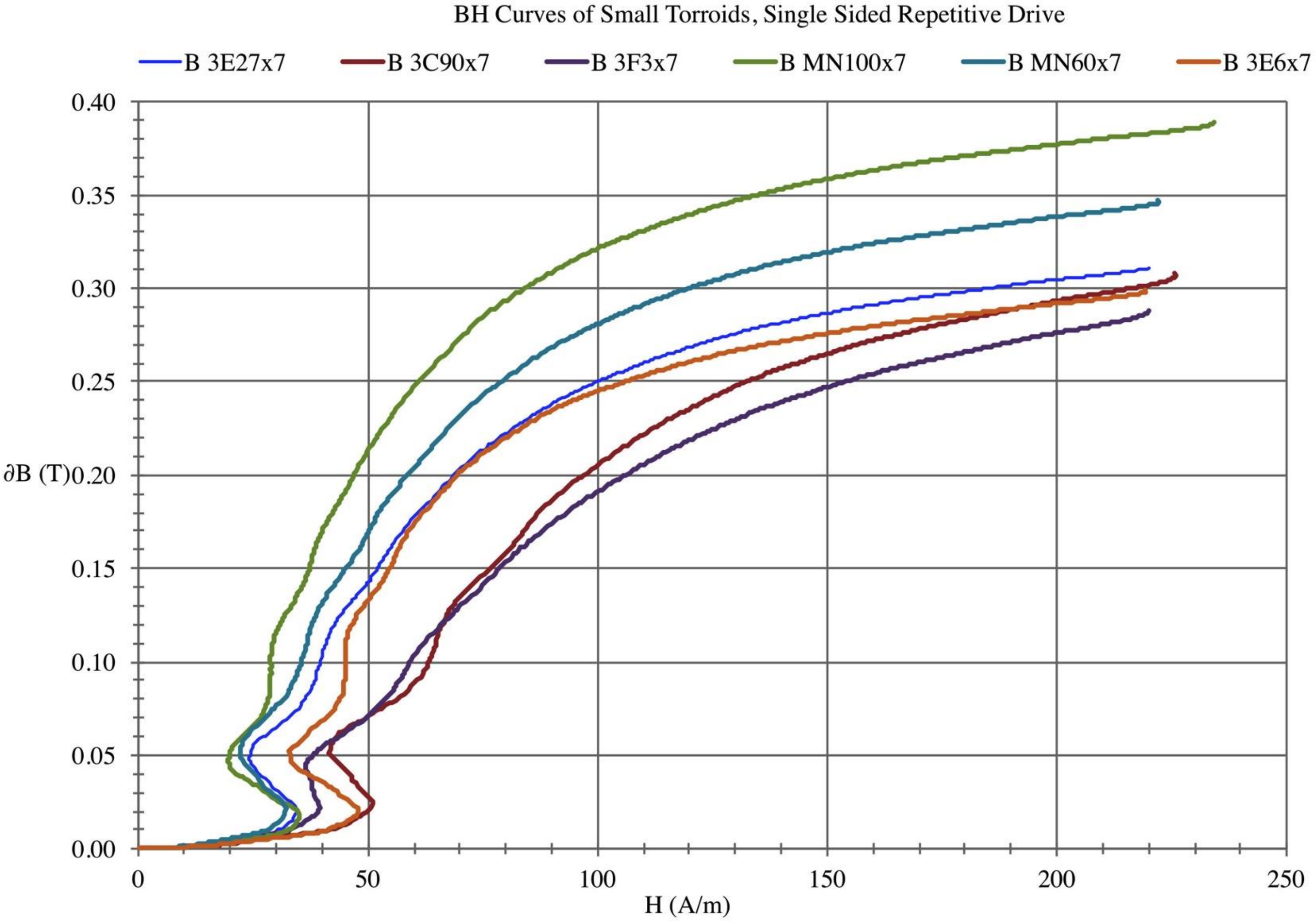
Material Measurements



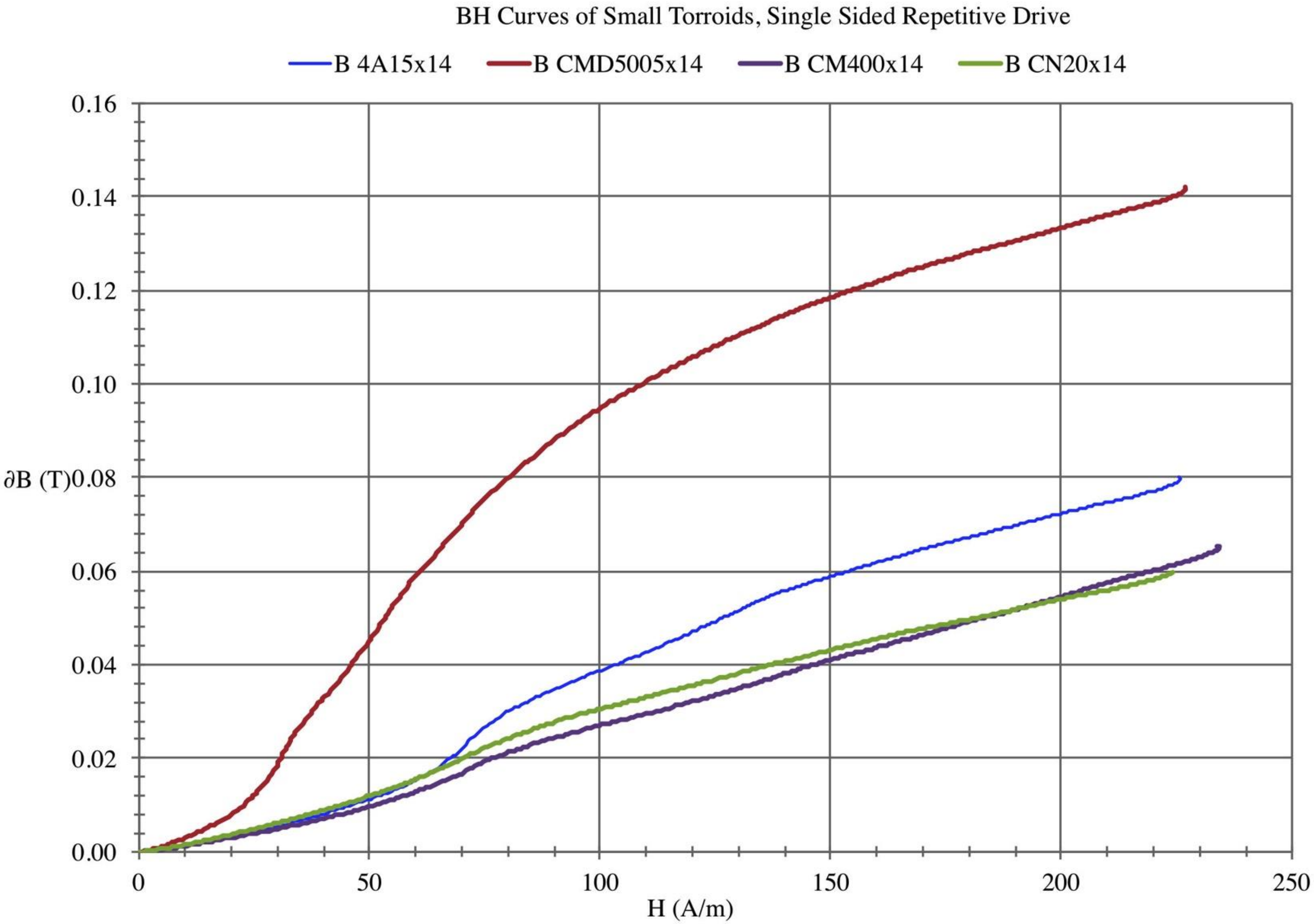
Material Measurements



Material Measurements



Material Measurements



Examples

- Consideration in choosing material
    - Is the space limited? Is the material available in size required?
    - Will there be a way to reset field after pulse? Does cost and size mean field reset is a requirement? Can an air gap be used as part of reset mechanism?
    - Does the field need to be uniform in an application that interacts with beam? Will saturation effect field uniformity? How much?
    - Is a custom shape needed? Can it be fabricated using any material?
    - Is this a fast repetition rate? What are losses in material?
    - Is the voltage applied enough to dielectrically breakdown ferrite? Should laminations be used? Should ferrite be insulated?
    - How much do material properties vary by lot? Is that a problem? Are there multiple manufacturers of similar material?
    - Other mechanical properties (vacuum, heat conduction, radiation tolerance, toughness)

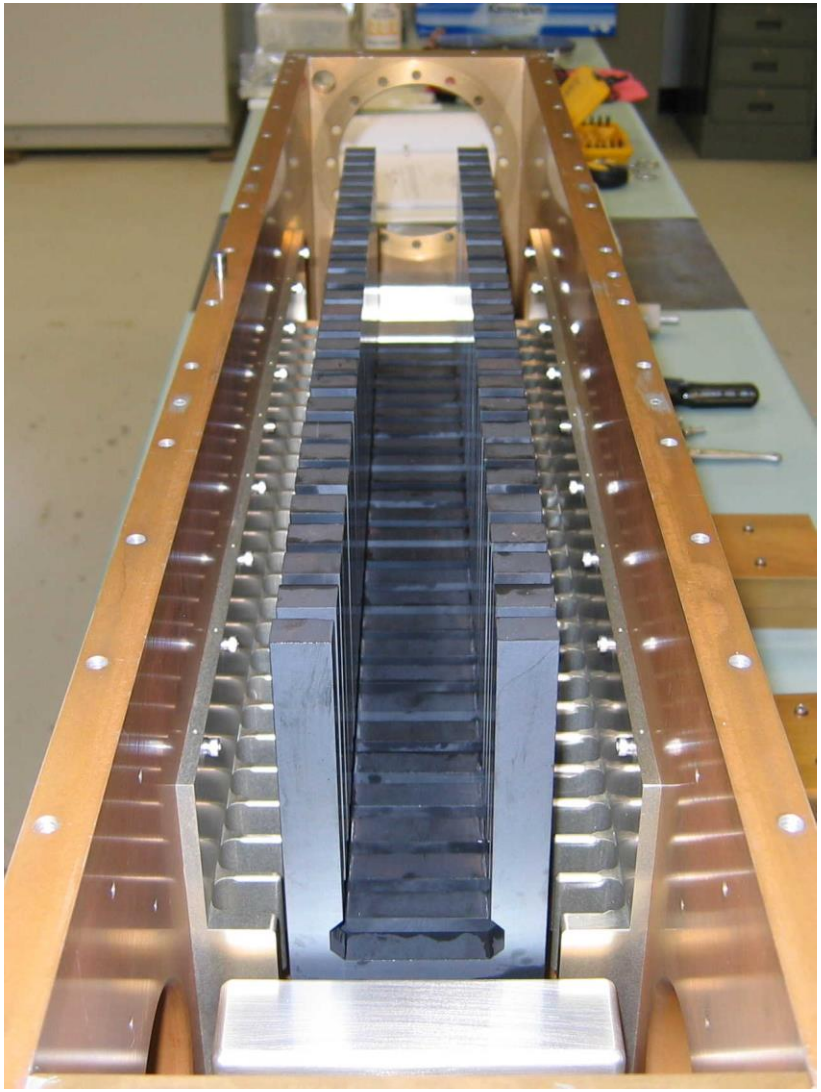
Example 1 – Injection Kicker Magnet

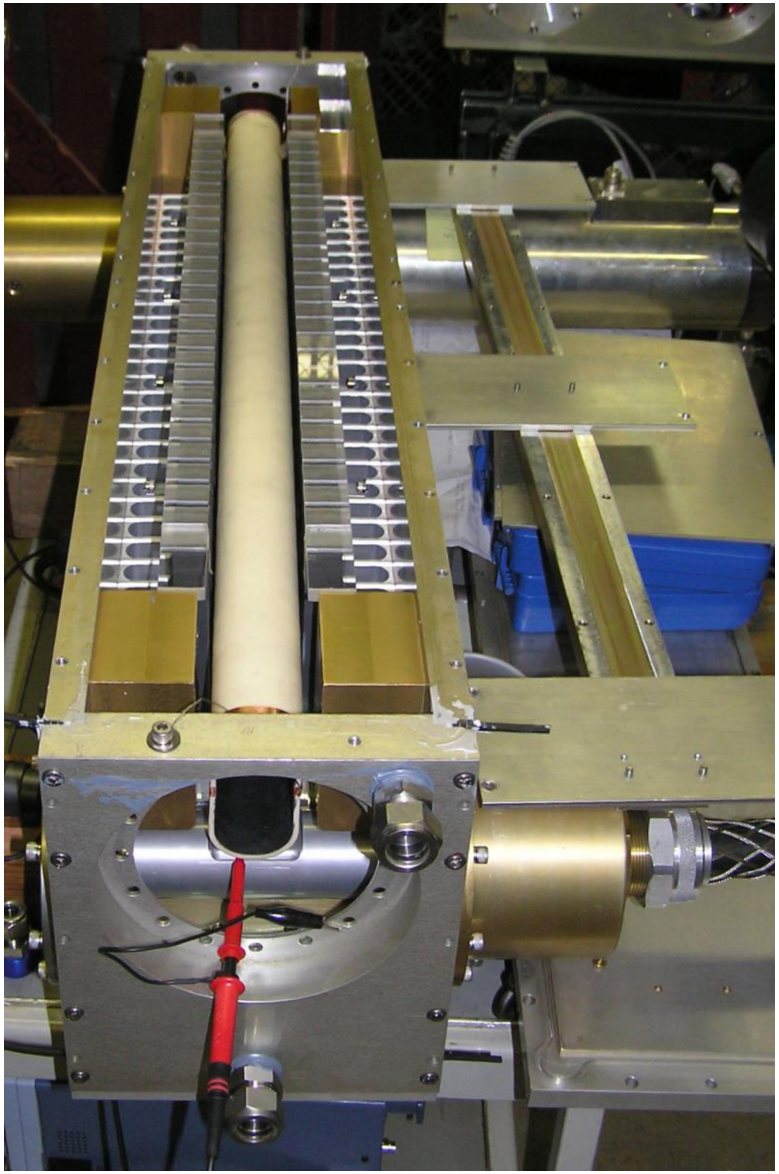
- Considerations in choosing material
  - Gap for beam in ferrite, will naturally reset to small residual field
  - Fast rise time implies lower permeability ferrite required

    (NiZn, $\mu_i \sim 400$, $B_{sat} \sim 0.46$ T, $B_r \sim 0.25$ T, ρ 10^8 Ohm cm)

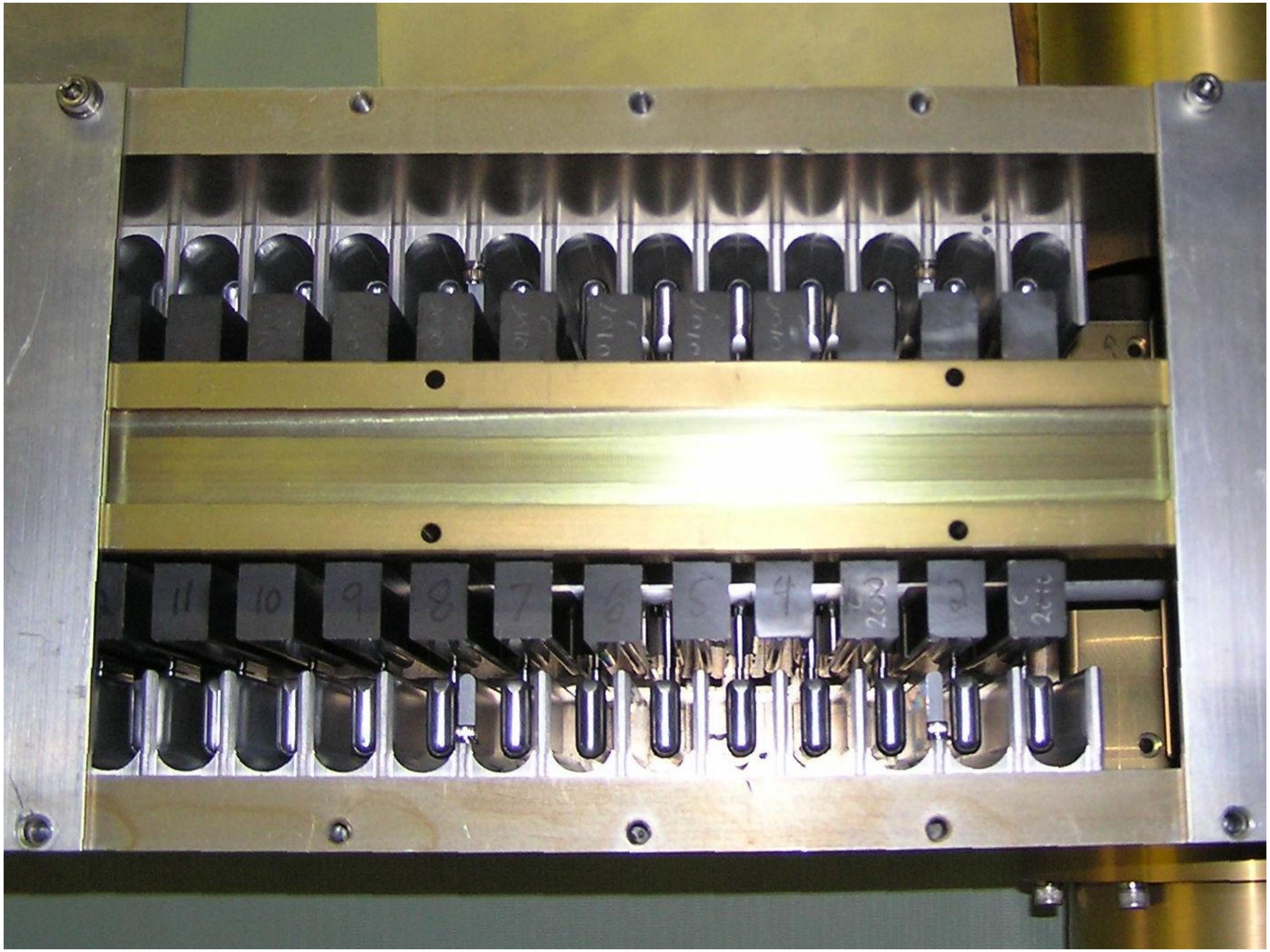
    $f_{max} = \gamma M_{sat} / (3 \pi (\mu_i - 1))$ is location of maximum loss [2]
  - Fast rise time also means limit cross section size to prevent resonance / standing wave
  - Field uniformity requirement is +/- 1%, so can accept some saturation in corners, limited B in ferrite to about 0.2 T
  - Repetition rate is low, duty factor low, some loss in ferrite can actually damp cell to cell resonances
  - High applied voltage, but ferrite does not support voltage
  - Ferrite is not in vacuum for Fermilab designs
- See [3]

Example 1 – Kicker Magnet





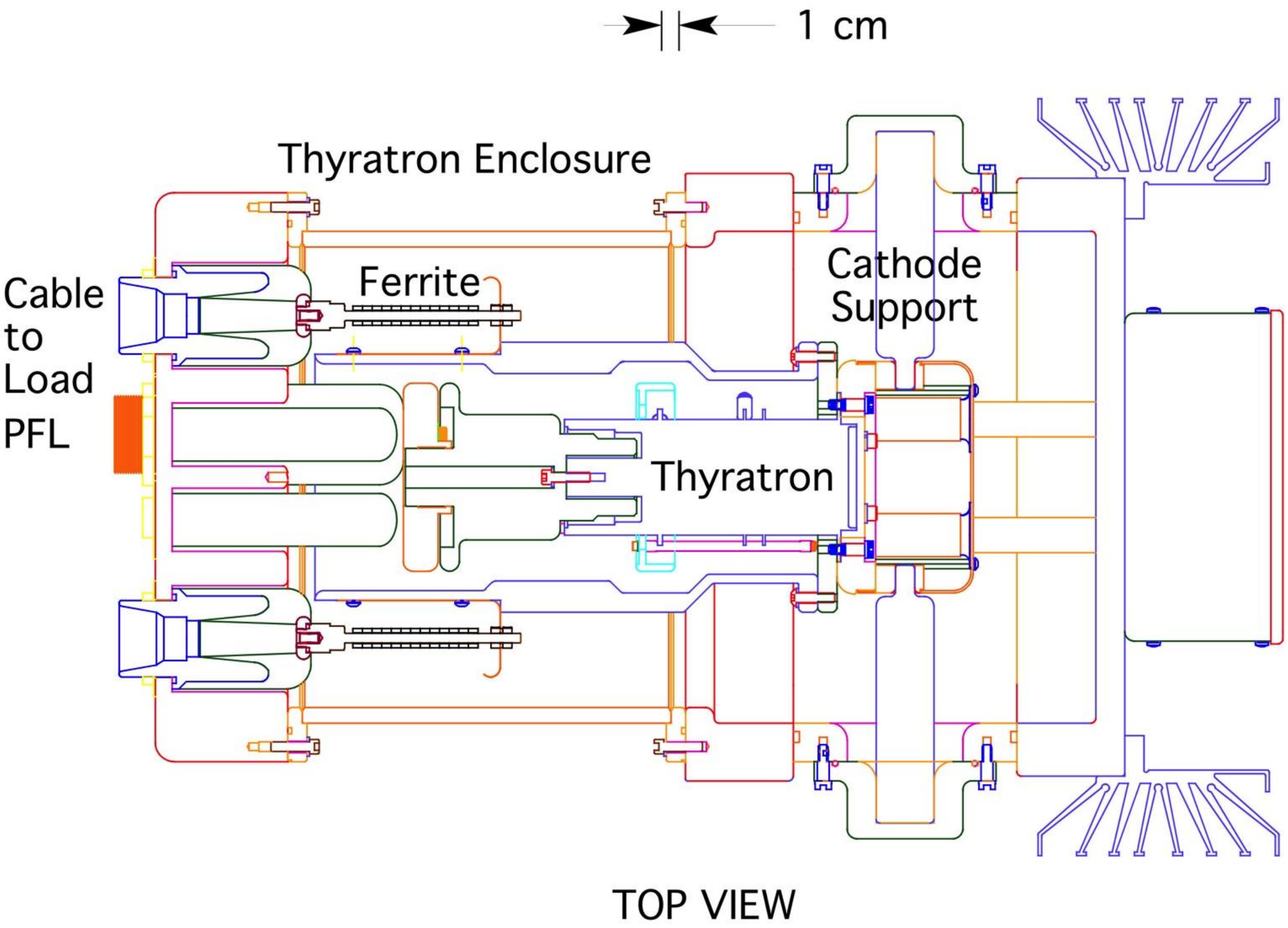
Example 1 – Injection Kicker Magnet



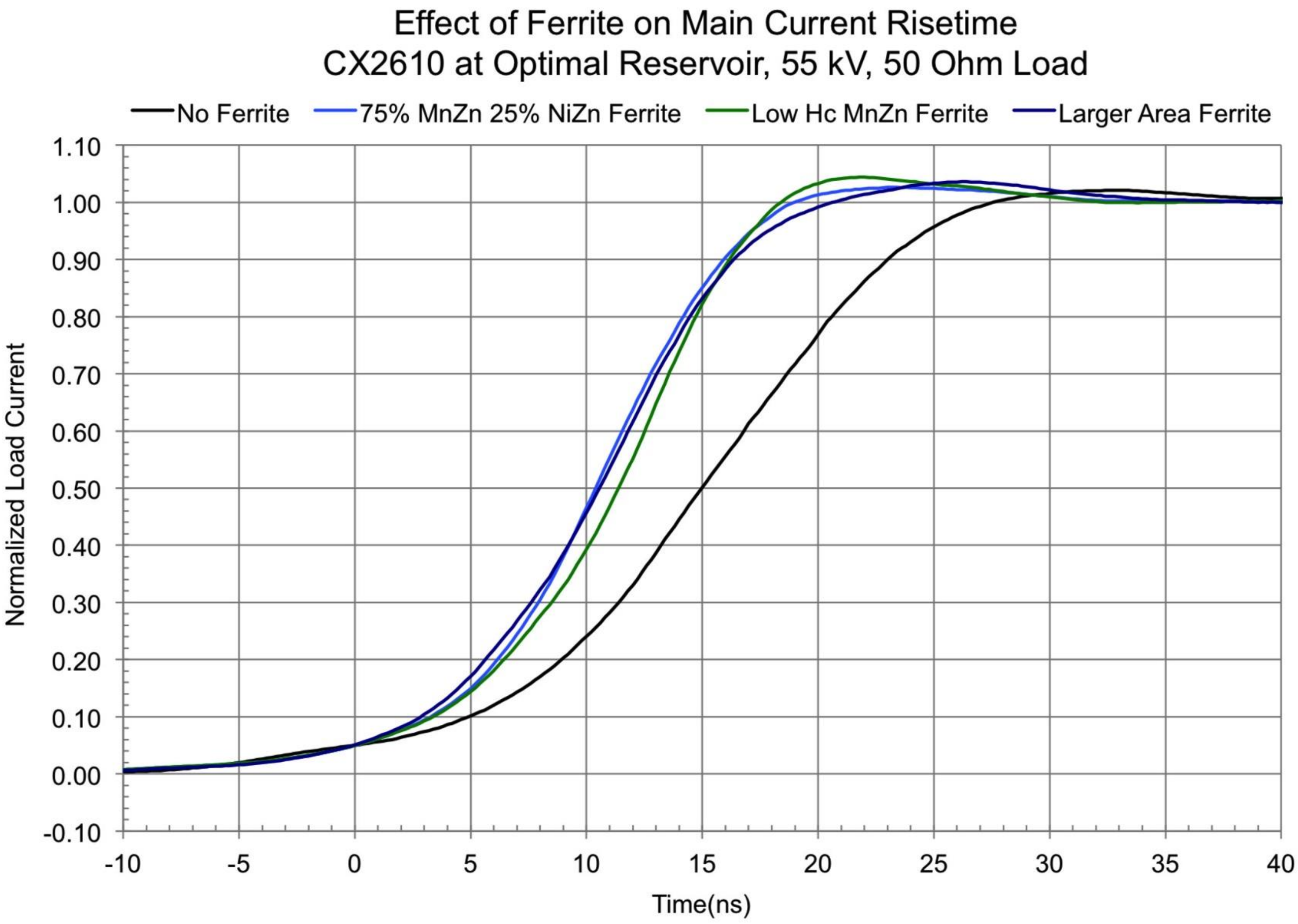
Example 2 – Saturating impedance for pulser

- Consideration in choosing material
  - No gap in core, but need 30 kV isolation and high impedance at very high speed, wont reset core
  - Since no reset, need low Br material
  - Unsaturated core needs to be high impedance, low Hc
  - Want core to saturate all at same time, small OD to ID ratio
  - Repetition rate is low, duty factor low, some loss in ferrite ok
  - High applied voltage, but along core surface not through ferrite
- See [4]

Example 2 – Saturating impedance for pulser

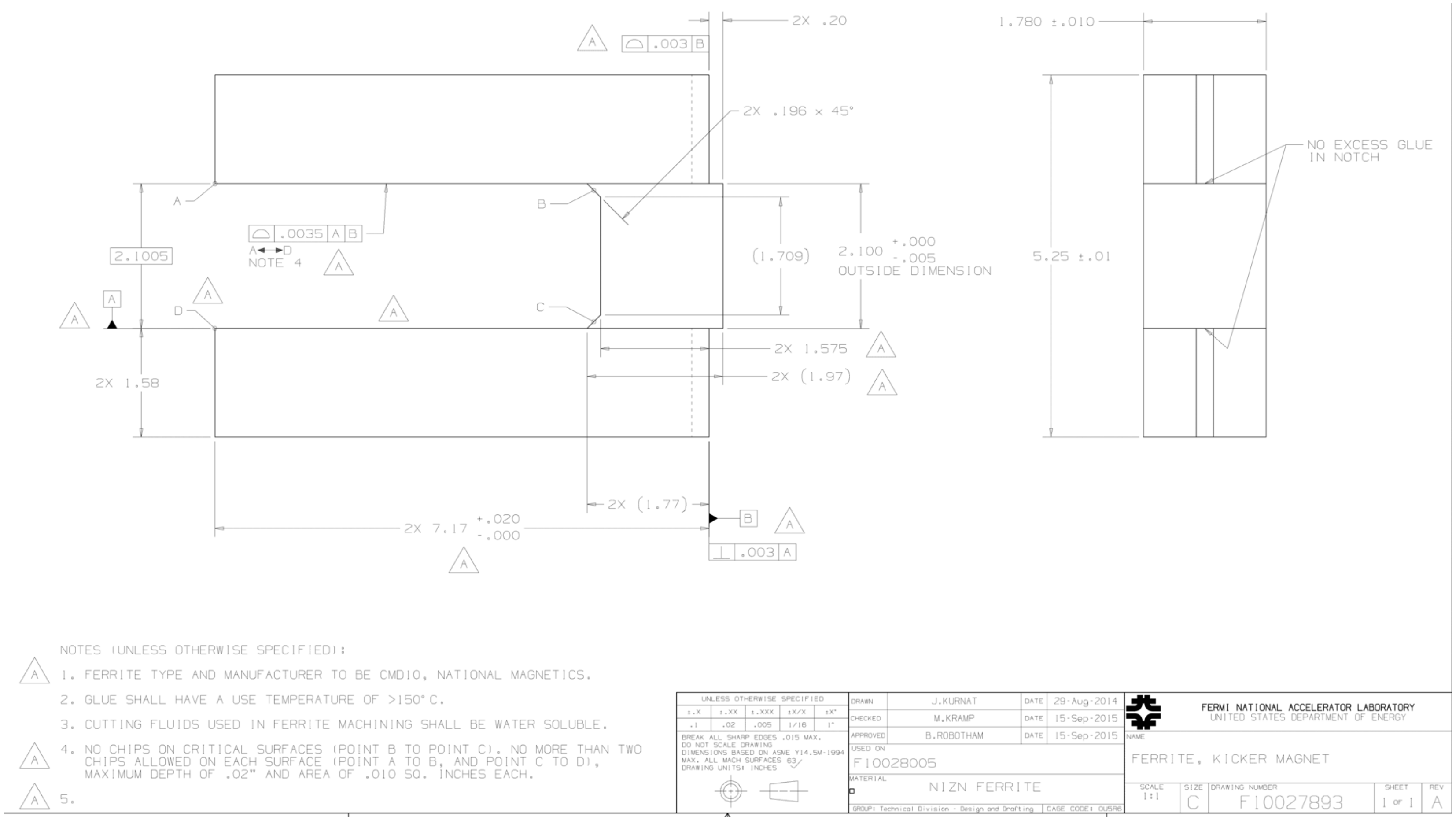


Example 2 – Saturating impedance for pulser



Recent Procurement Experience

- Consolidation of 2 American Companies into 1
  - Ceramic Magnetics bought by National Magnetics Group Inc. (Pennsylvania)
  - These are only companies that make large, machined shape ferrites; other companies for small toroid's
  - Lead times have been very long recently for CMD5005 and CMD10 (both NiZn kicker ferrites)
- European Companies
  - Ferroxcube (Poland and China), Others?
- Asian Companies
  - TDK, ?
  - China ?



NOTES (UNLESS OTHERWISE SPECIFIED):

1. FERRITE TYPE AND MANUFACTURER TO BE CMD10, NATIONAL MAGNETICS.
2. GLUE SHALL HAVE A USE TEMPERATURE OF >150° C.
3. CUTTING FLUIDS USED IN FERRITE MACHINING SHALL BE WATER SOLUBLE.
4. NO CHIPS ON CRITICAL SURFACES (POINT B TO POINT C). NO MORE THAN TWO CHIPS ALLOWED ON EACH SURFACE (POINT A TO B, AND POINT C TO D), MAXIMUM DEPTH OF .02" AND AREA OF .010 SQ. INCHES EACH.
5.

UNLESS OTHERWISE SPECIFIED

±.X	±.XX	±.XXX	±X/X	±X°
.1	.02	.005	1/16	1°

BREAK ALL SHARP EDGES .015 MAX.
DO NOT SCALE DRAWING
DIMENSIONS BASED ON ASME Y14.5M-1994
MAX. ALL MACH SURFACES 63
DRAWING UNITS: INCHES

DRAWN	J.KURNAT	DATE	29-Aug-2014
CHECKED	M.KRAMP	DATE	15-Sep-2015
APPROVED	B.ROBOTHAM	DATE	15-Sep-2015

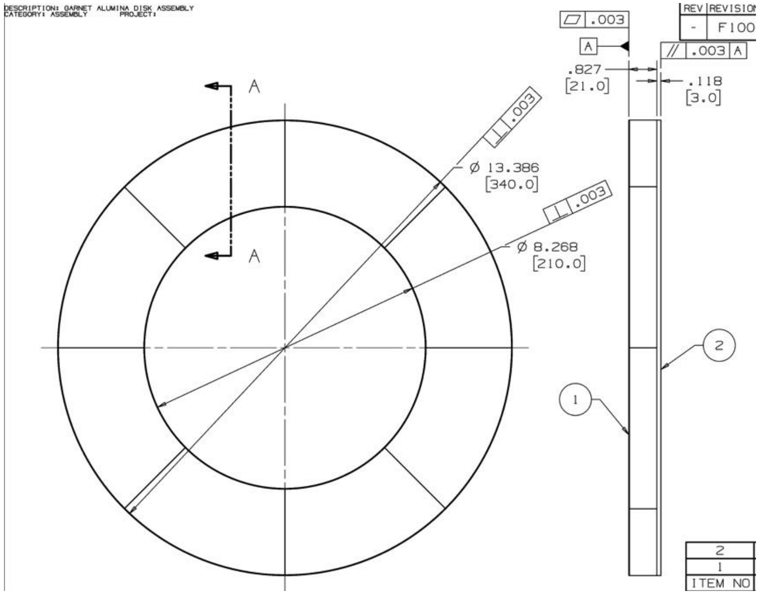
USED ON F10028005
MATERIAL NIZN FERRITE
GROUP: Technical Division - Design and Drafting
CAGE CODE: 0U5R6

FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY

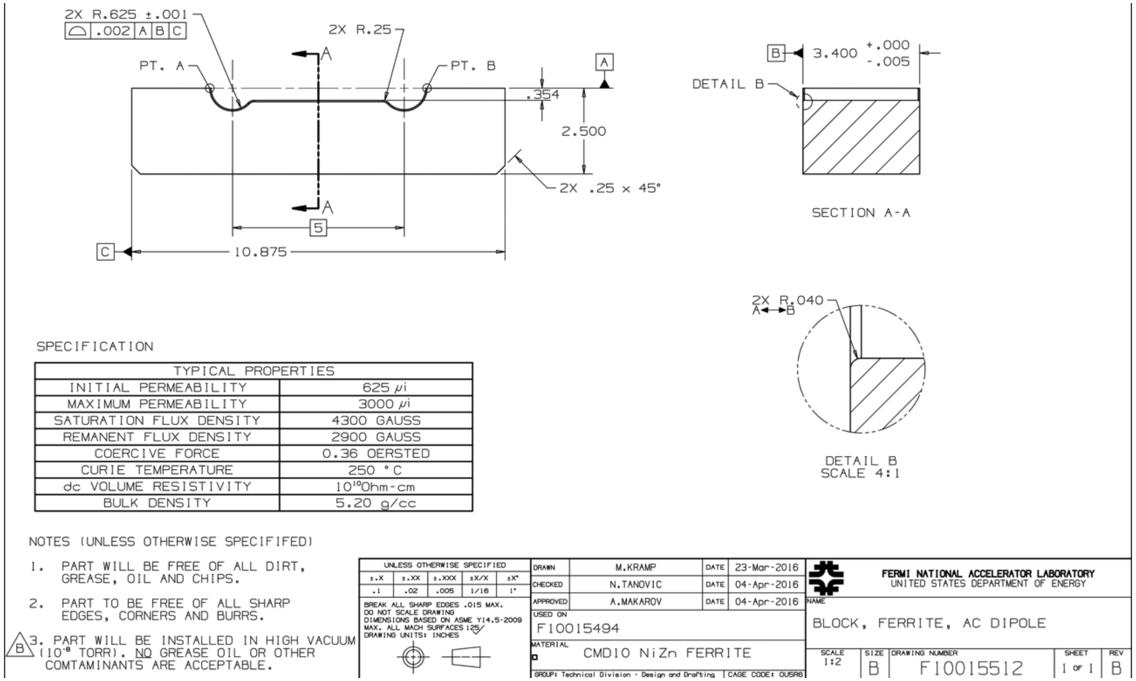
NAME FERRITE, KICKER MAGNET

SCALE	SIZE	DRAWING NUMBER	SHEET	REV
1:1	C	F10027893	1 OF 1	A

Sample 1 for kicker magnet, multiple glued pieces, CMD10
20 pieces ordered, Delivery ~ 15 months



Sample 2 for RF tuner, 8 pieces glued onto alumina substrate, AL-8 garnet
5 assemblies ordered
Delivery ~ 9 months



SPECIFICATION

TYPICAL PROPERTIES	
INITIAL PERMEABILITY	625 μi
MAXIMUM PERMEABILITY	3000 μi
SATURATION FLUX DENSITY	4300 GAUSS
REMANENT FLUX DENSITY	2900 GAUSS
COERCIVE FORCE	0.36 OERSTED
CURIE TEMPERATURE	250 °C
dc VOLUME RESISTIVITY	10^{10} Ohm-cm
BULK DENSITY	5.20 g/cc

NOTES (UNLESS OTHERWISE SPECIFIED)

1. PART WILL BE FREE OF ALL DIRT, GREASE, OIL AND CHIPS.
2. PART TO BE FREE OF ALL SHARP EDGES, CORNERS AND BURRS.
3. PART WILL BE INSTALLED IN HIGH VACUUM (10^{-8} TORR). NO GREASE OIL OR OTHER COMTAMINANTS ARE ACCEPTABLE.

Sample 3 for 3 MHz AC magnet, single piece machined profile, CMD10
20 pieces ordered
Delivery ~ 12 months

References

- [1] E.C. Snelling, Soft Ferrites, Properties and Applications, 2nd Edition, 1988 Butterworth & Co
- [2] J. L. Snoek, Dispersion and absorption in magnetic ferrites at frequencies above 1 Mc/s, Physica Amsterdam, Vol. 14, 1948
- [3] C.C. Jensen, R. Reilly, I. Terechkine, Gap Clearing Kicker Magnet for Main Injector, PAC 2009, Vancouver, BC, Canada, pp 1729-1731
- [4] C.C. Jensen, Kicker Pulsers for Recycler Nova Upgrades, IPAC 2015, Richmond VA, WEPTY027
- [5] Richard M. Bozorth, Ferromagnetism, 1993 Wiley Press