Core Alloy Evaluation for HIF Induction Accelerators

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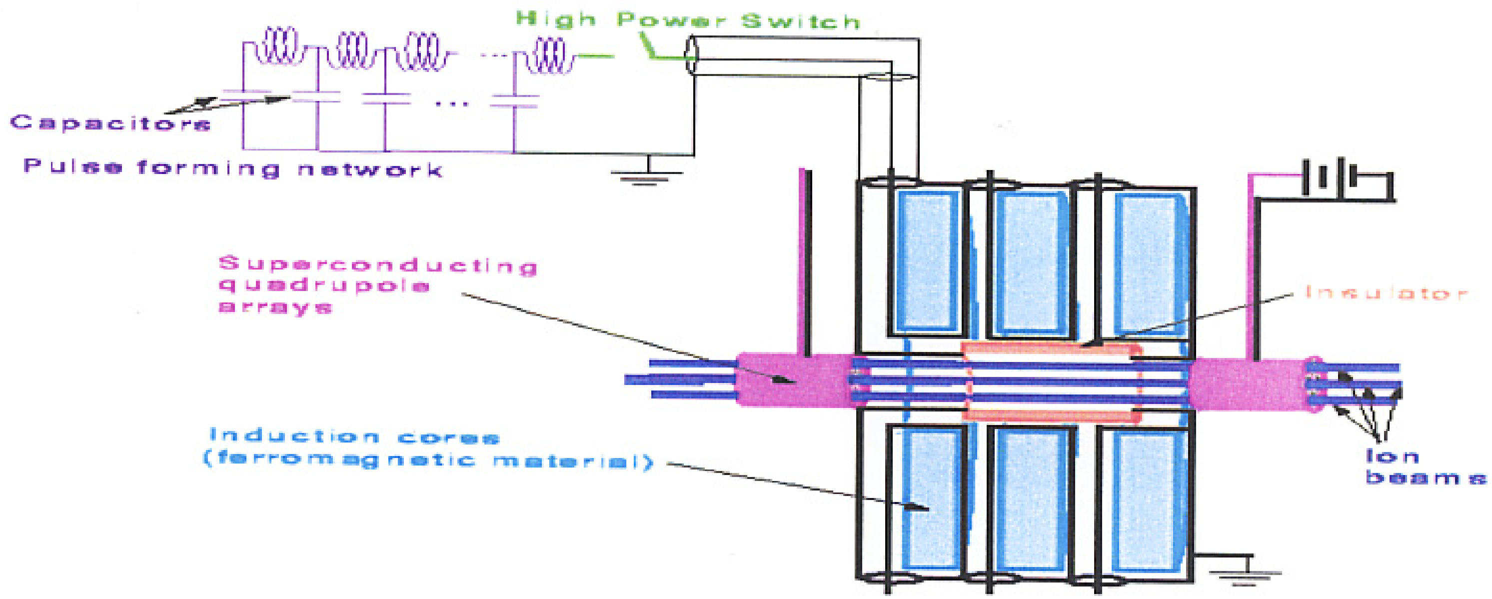
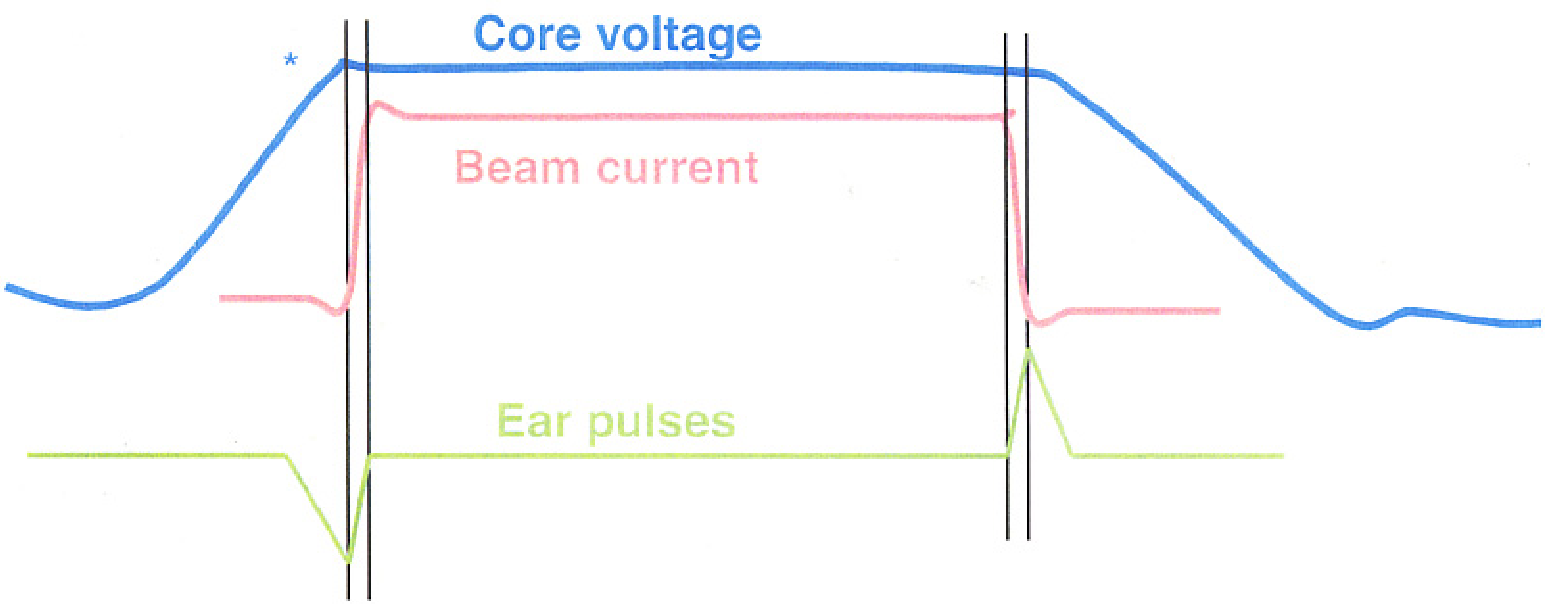
Induction linacs can accelerate and transport high beam currents for HIF



- Primary voltage waveform is induced along beam, through a vacuum barrier insulator.
- One candidate pulser geometry shown.
- Superconducting quadrupole magnets will transport the beam through most of the length of a driver.

Core flux swing must include rise and fall of the beam in pulse flattop



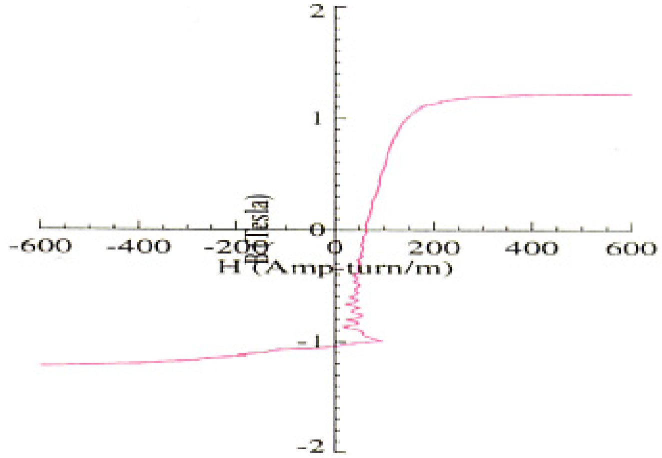
Ear pulses provide longitudinal confinement of beam

* If final rise of V_{core} is properly matched to beam risetime, it may serve as front ear pulse.

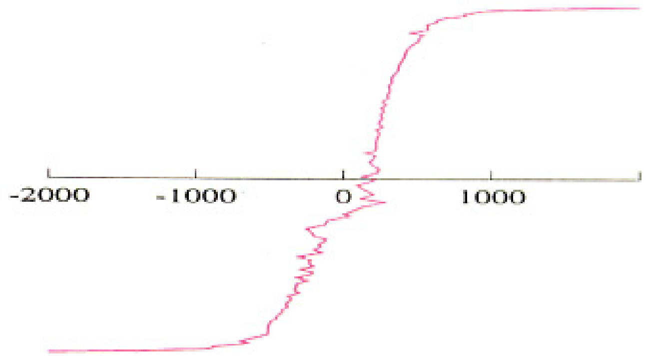
Remanent and saturation fields measured

Core first pulsed from - B_r to + B_s, then the leads are reversed, the reset turned off, and the core is pulsed from - B_r to - B_s.

(a) A partial hysteresis loop for nanocrystalline core with high B_r/B_s. This core will yield relatively high flux swings, even with lower B_s. (VACUUMSCHMELZE VITROPERM core manufactured by National-Arnold Magnetics.)



(b) A METGLAS 2605 SA1 core has been potted in silicone rubber, the mechanical stress significantly reduces B_r. Such a core will give a lower flux swing then one with higher B_r.



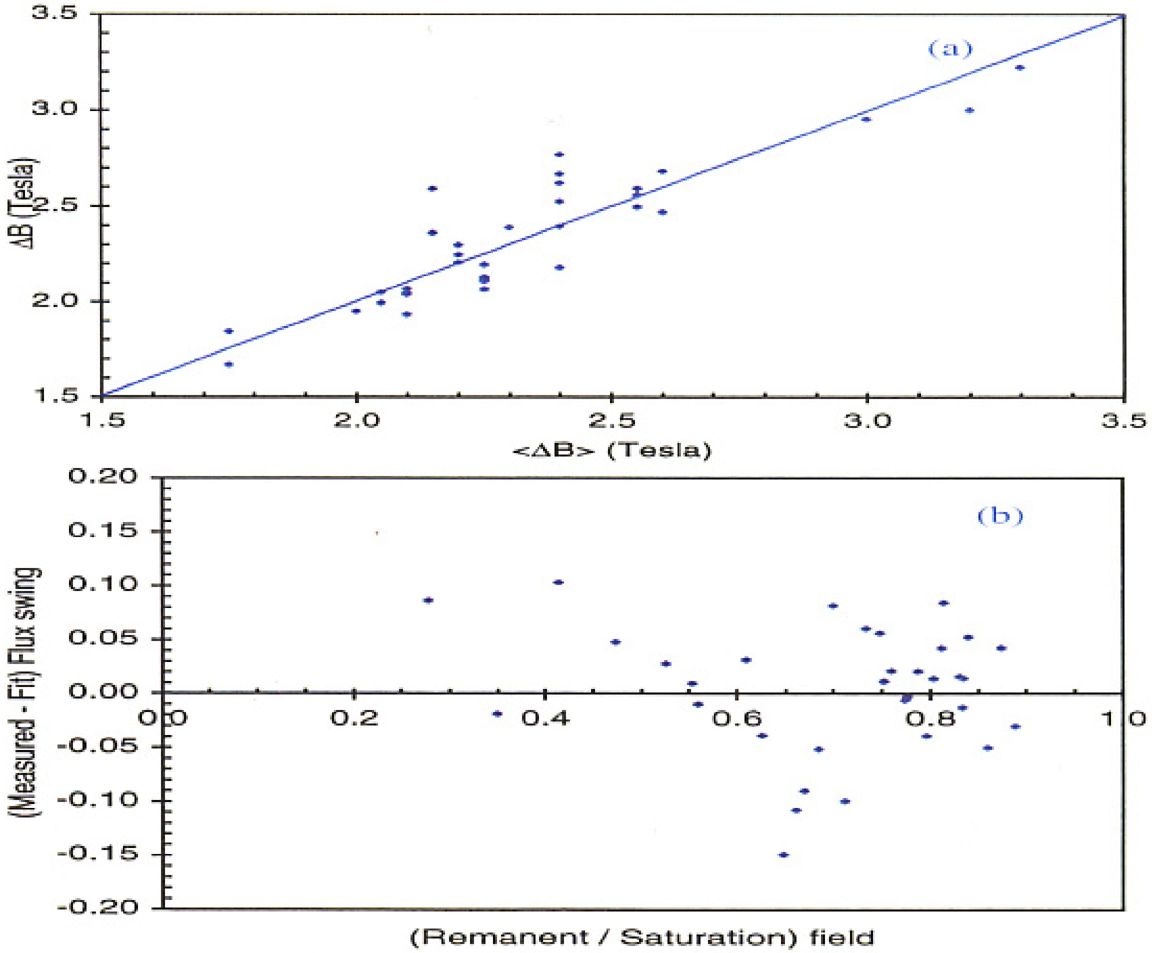
Large back bias current yields a flux swing approaching $2B_s$, but losses increase

Flux swing is function of B_r & B_s

$$\Delta B_{fit} = B_r + C_0 B_s$$
$$C_0 = 0.81 \pm 0.10$$

(a) ΔB_{fit} is compared with measured flux swing <ΔB>. For high flux swing with minimum loss, we need both B_r and B_s large.

(b) No consistent variation of ΔB_{fit} with B_r/B_s shows no higher order fit needed.

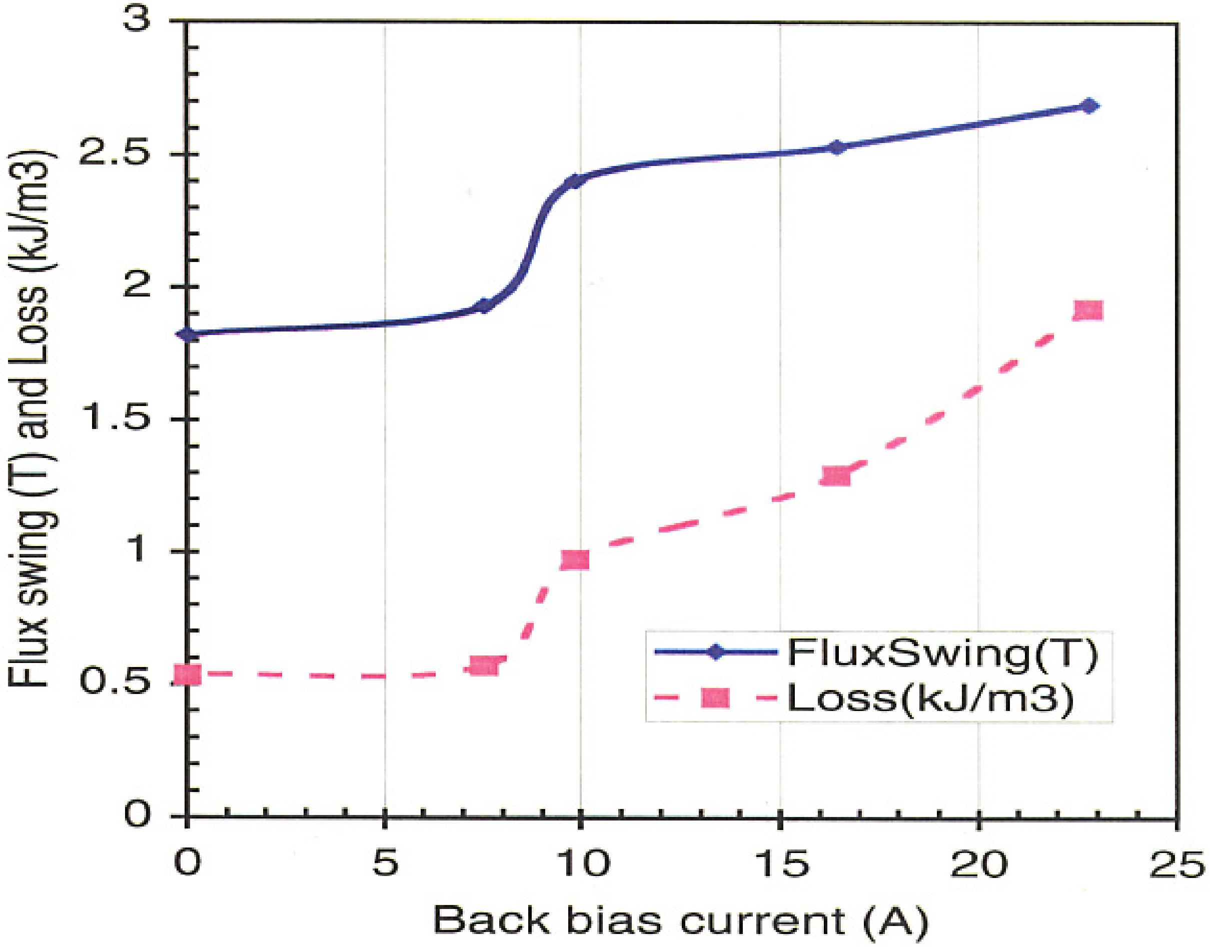


Back bias can increase flux swing, especially if high loss allowable

Core has $B_r/B_s = 0.45$.

Small back-bias current can increase flux swing ~10% with similar increase in core loss.

With large back bias current, the flux swing can increase to **0.8 to 0.9 x 2 B_s**, but the core loss increases by a factor of several.



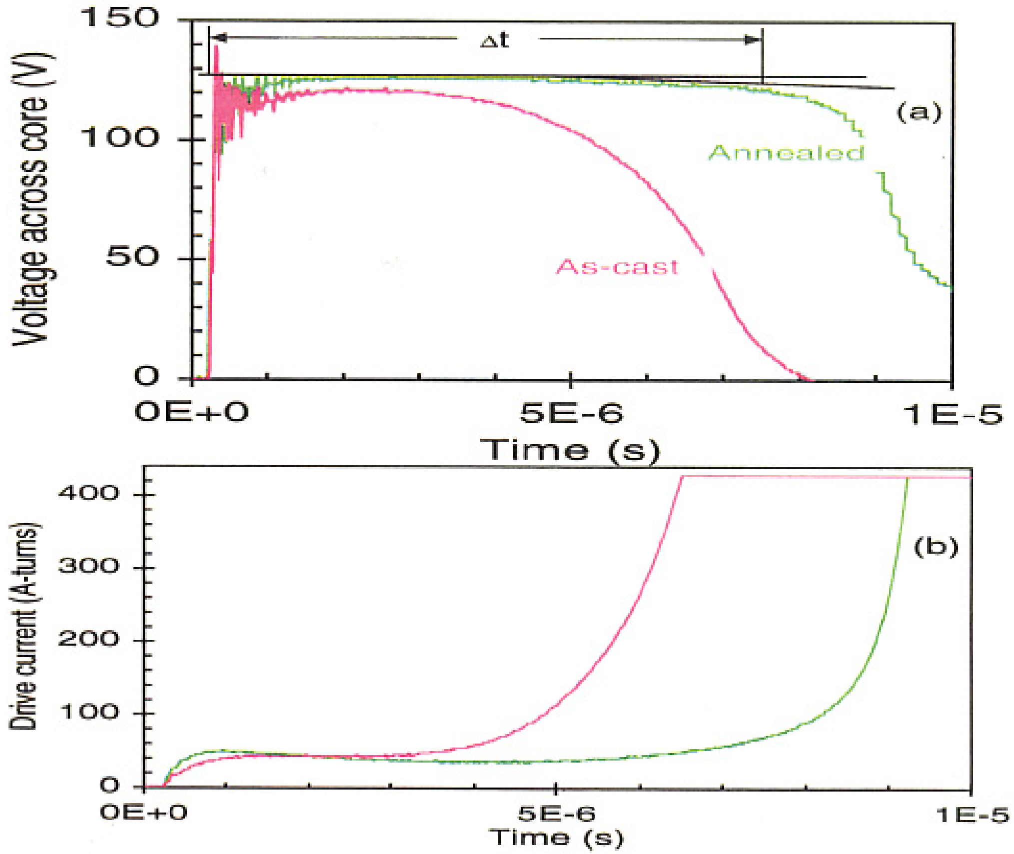
Core made by MRTI, with Russian alloy 7421

Magnetic annealing increases B_r for higher flux swing with low loss

Other advantages:

- Easier to get flat-topped pulse with simple pulser.

- More reproducible core performance. Unannealed cores vary by 14-30% (RTA), annealed cores by ≤10%standard deviation.



METGLAS 2605 SC, insulated with co-wound mica paper

A range of magnetic materials are applicable to HIF

- Applicable to long pulse durations near injector

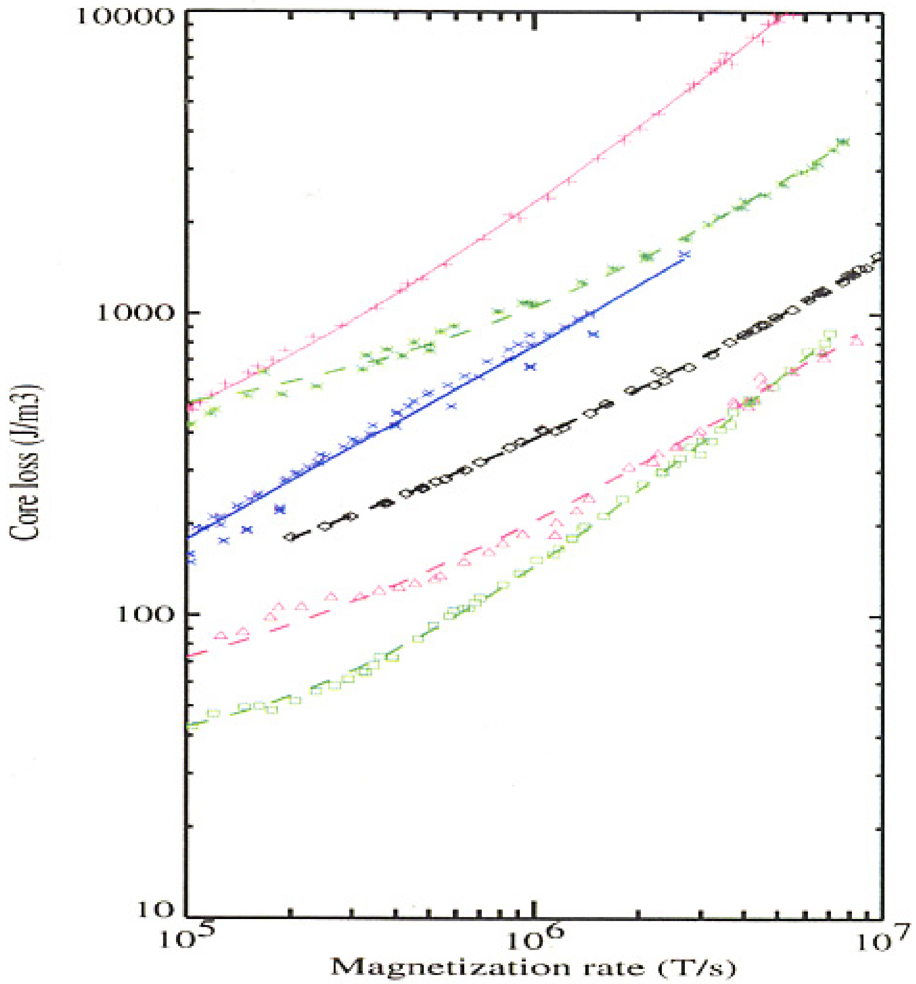
+ 50 μm 3% SiFe 3.3T
* 25 μm 3% SiFe 3.0T

- Generally applicable

x 2605 SA1 METGLAS (2.2) - 2.7 T
◊ 2605 SC METGLAS (2.2) - 2.4 - (2.7) T

- Applicable to correction pulsers, or other applications where low loss is crucial

Δ FINEMET FT-2H 2.4T
□ FINEMET FT-1H 2.1T



Proposed Industrial policy motivated examining SiFe and FINEMET alloys

Ideal – 3 or more suppliers

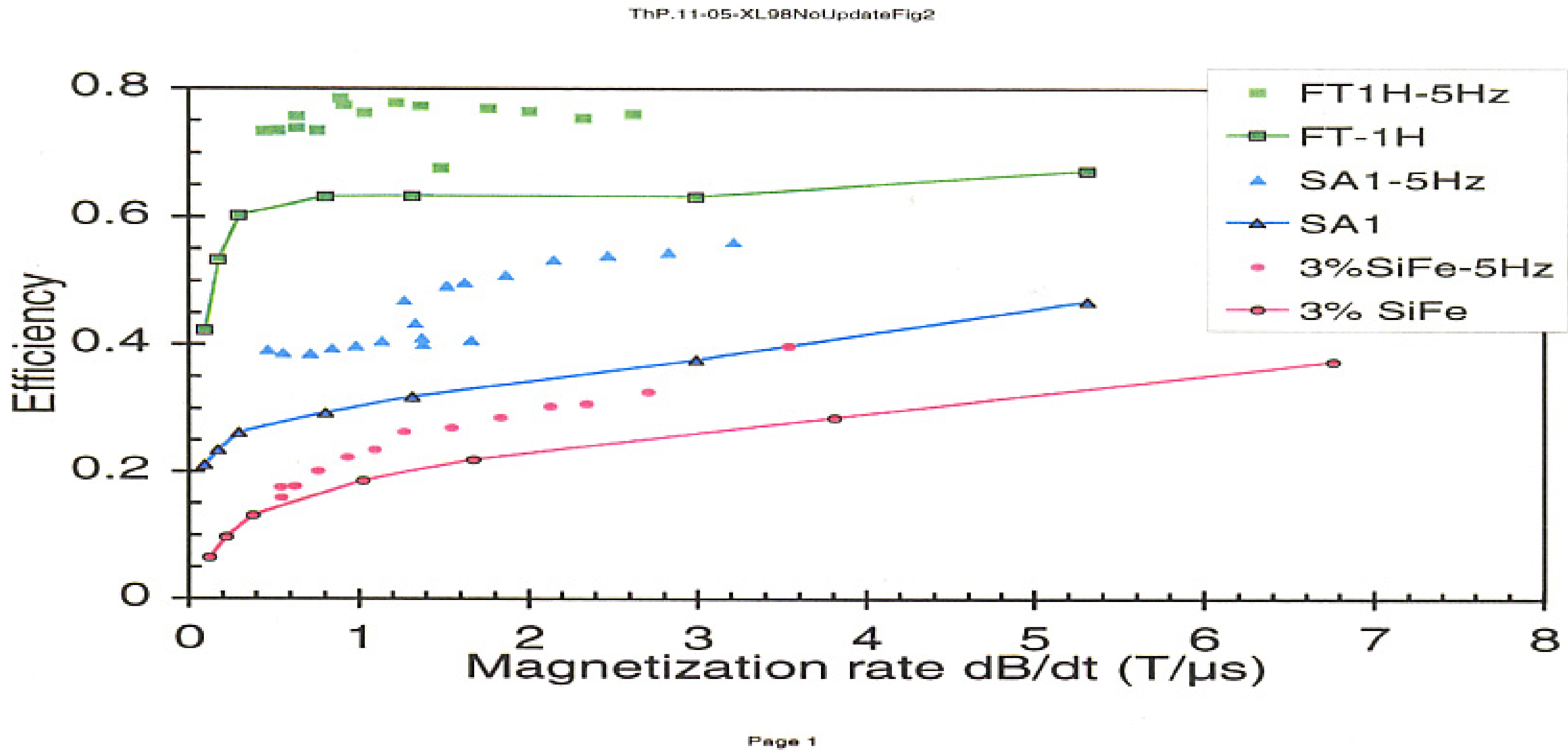
Near Term:

- Honeywell (formerly AlliedSignal) METGLAS performs well enough and is potentially much cheaper, so it could supply most to all of our needs.[but only 1 supplier]
- We can erode its market share from 100% to 60-90% by finding applications for other materials.
  - SiFe [0r 2605 CO] reduces core mass near injector where pulses ~10μs
  - Nanocrystalline for correction cores (where pulsers are very expensive).
- We can also have other companies manufacture cores from METGLAS.

Long term: (10-30 years)

- Patents expire. Other companies, such as Hitachi, may develop continuous casting and can compete in price in both amorphous and nanocrystalline alloys.
- Major companies construct plants in countries where needed, reducing transportation costs.

Higher flux-swing alloys reduce core mass but increase pulser power



- Even 3% SiFe throughout driver results in marginally acceptable efficiency

- Used only near injection, 50 μm 3%SiFe could reduce the core mass by 100-800 metric-tons, at expense of increasing average pulser power by 0.2-0.6 MW out of total 20-40 MW.

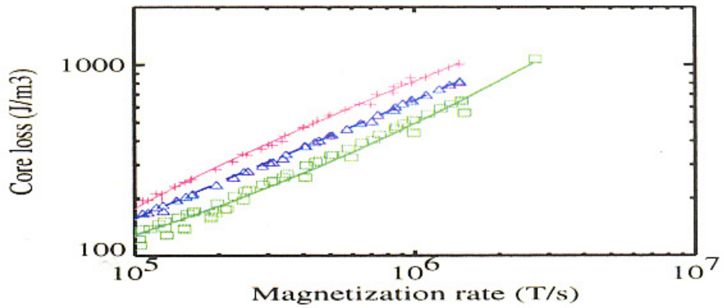
METGLAS 2605 SA1 developed for low cost 60 Hz, yet good for pulsed

NAM Mg-Methylate thin-coat

(x) 2.7 T

(Δ) 2.5 T

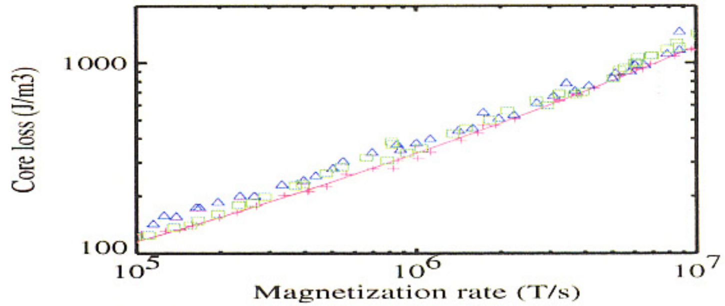
(□) 2.2 T



(Δ) Thin SA1-3 2.10 T

(□) Thin SA1-4 2.10 T

(+) Thin SA1-2 2.10 T

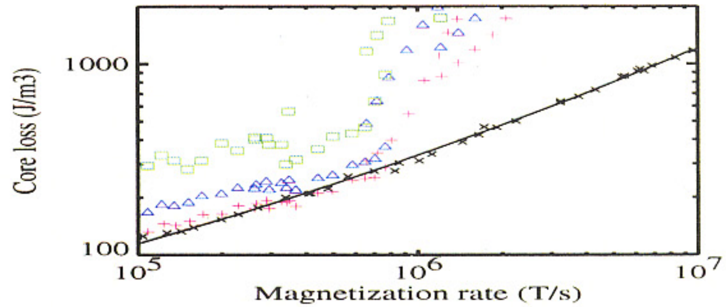


(□) Th NAM SA1-2 2.65 T

(Δ) Th NAM SA1-2 2.40 T

(+) Th NAM SA1-2 2.10 T

(x) Th MRTI SA1-2 2.10 T



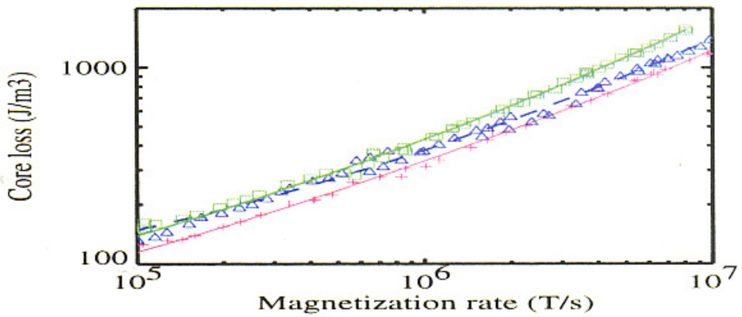
2605 SC and SA1 perform similarly, Thin SA1 especially promising

MRTI (Moscow Radio-Technical Institute)

(□) SA1-2 2.10 T

(Δ) SC-01 2.20 T

(+) Thin SA1-2 2.10 T

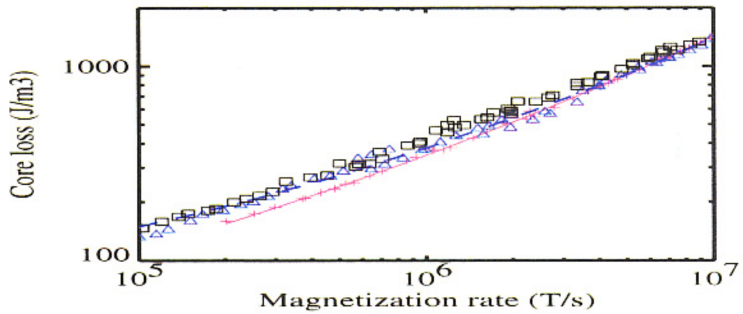


MRTI

(□) SC-02 2.25 T

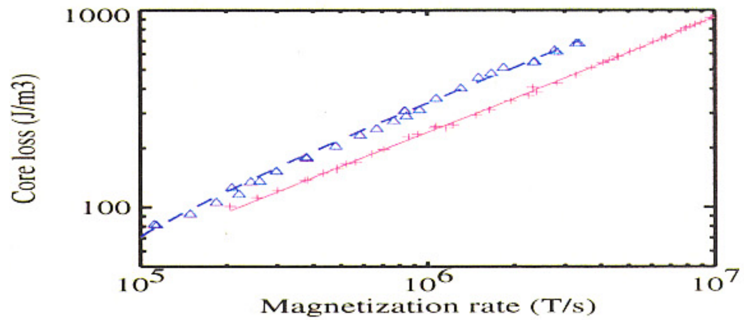
(Δ) SC-01 2.20 T

(+) Mica C-14 2.25 T

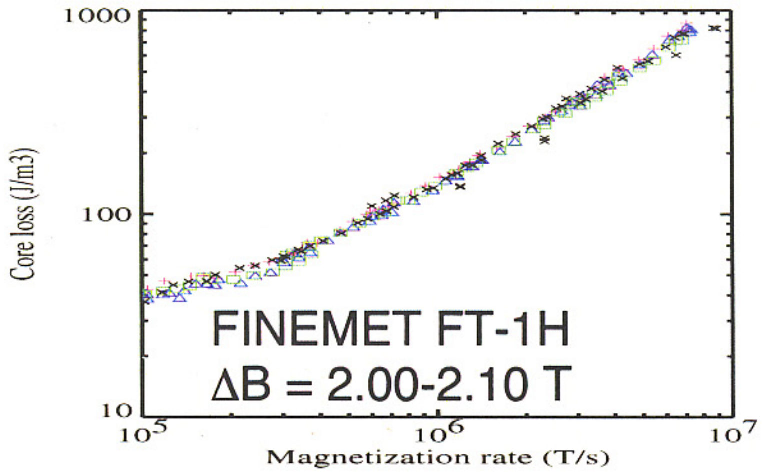


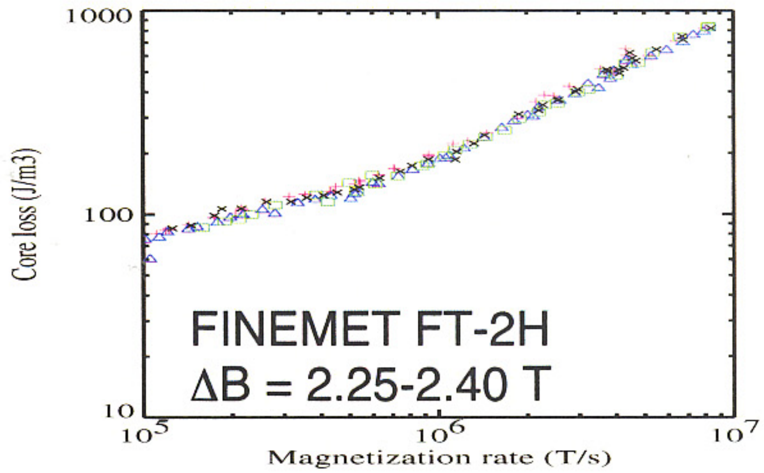
(Δ) SC Annealed and rewound, max - 1.60 T

(+) Mica C-14 @ 1.60 T



Nanocrystalline have significantly lower loss, slightly lower flux swing





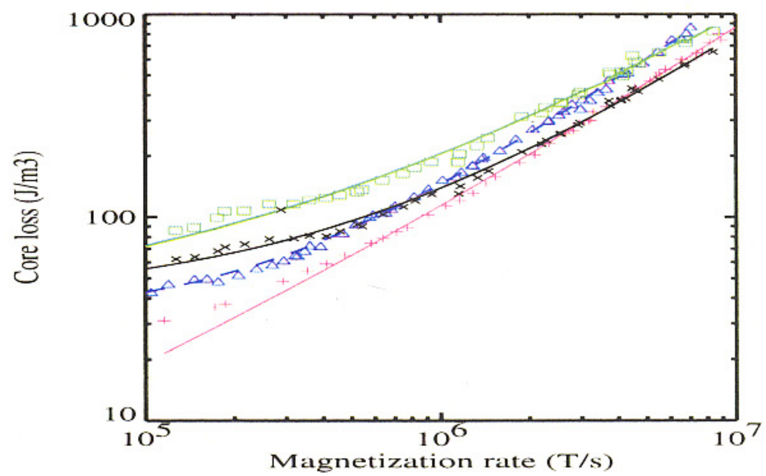
FINEMET compared with Vacuumschmelze VITROPERM cores manufactured by National-Arnold Magnetics

(□) FT-2H 2.40 T

(x) FT-2H 2.10 T

(Δ) FT-1H 2.10 T

(+) NAM-VAC 2.10 T



3% SiFe, 25-50 μm thick, reduces core mass but increases losses

100 μm losses too high

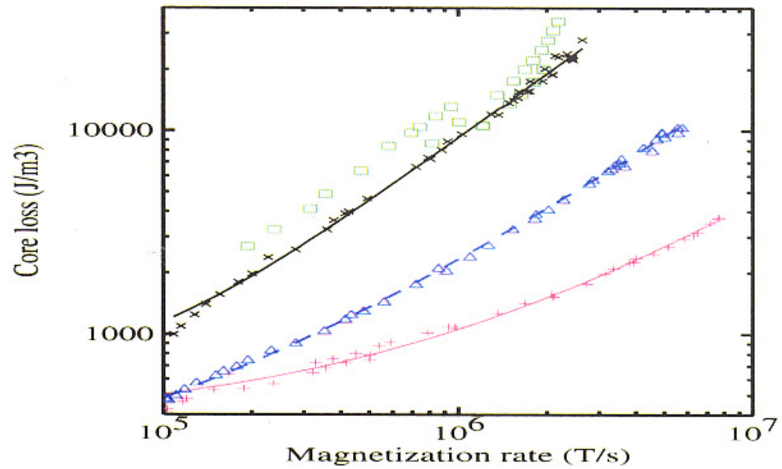
(▭) 100 μm 3.20 T

(x) 100 μm selected 3.30 T

(Δ) 50 μm 3.30 T

25 μm losses slightly greater than with METGLAS 2605 CO

(+) 25 μm 3.00 T



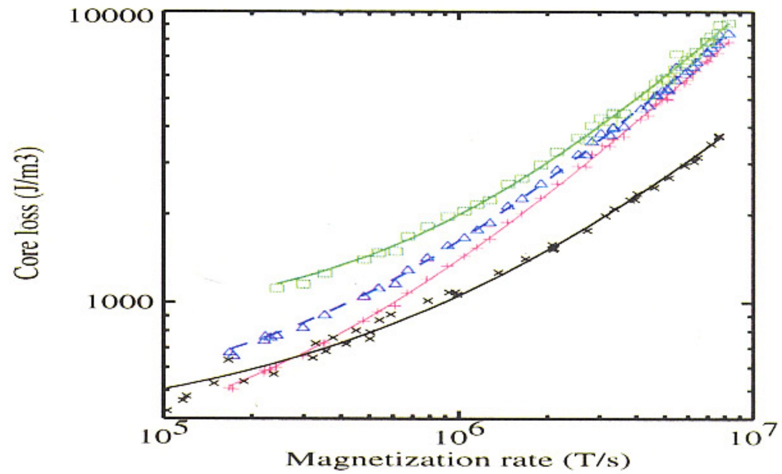
3% SiFe offers higher flux swing with lower loss. No reason to use 6% SiFe

(▭) 6% SiFe 2.60 T

(Δ) 6% SiFe 2.50 T

(+) 6% SiFe 2.40 T

(x) 3% SiFe 25 μm 3.00 T



Requirements on interlaminar insulation

1. Voltage holding – 0.1 - 100 V/lamination
2. Withstand annealing temperature (amorphous – 325-400° C, nanocrystalline ≥550 ° C).
3. Apply minimal mechanical stress to alloy.
4. Thin (≤2-3 μm) for high packing fraction
5. Potential of low cost for materials and application
6. Lifetime of 10^{10} pulses (for 30 year life at 5-10 Hz)
7. Alloy and insulation separable for recycling at end of life

Coating preferable to co-wound tape insulation
- **Simpler winding**
- **Thinner for higher packing fraction**
- **No overhang at edges, easier to cool, and to anneal on side**

Status of induction core issues

Issue	Amorphous	Nano-crystalline	Silicon steel
Interlaminar voltage holding	Fair ↕ or Good ↕	Good	Good
High B_r/B_s	Good ↕ or Fair ↕	Good	Good
Consistency -reproducibility	Good	Good	Good
Cost today	Fair	Poor	Fair
Potential cost	Good	Good	Fair ?

Good	(green box)
Fair	(hatched blue box)
Poor	(empty pink box)