Conductors for Fast Ramping Accelerator Magnets

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Fast Ramping Dipole Magnets

Fast ramping magnets are important accelerator components in several areas

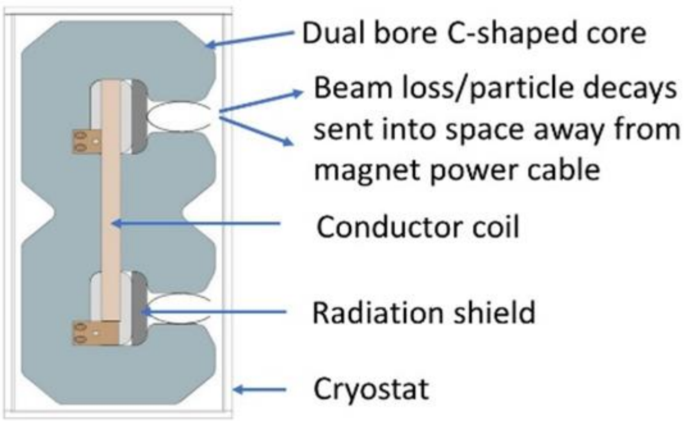
- High Energy Physics: accelerator ring for a Muon Collider, in booster accelerators for other colliders, and systems which produce high-intensity proton beams for high intensity targets
- Basic Energy Sciences: Part of system generating intense levels of irradiation for material science studies
- Fusion Energy Science: accelerator driven modular nuclear reactors
- Medical Applications: fast-cycling superconducting compact accelerator technology

Fast Ramping Dipole for Muon Collider

- Ideal specs for the accelerator of a muon collider is a dipole magnet that can reach 2 T with ramp rates >1000 T/s.
- This amounts to (assuming 2 T and 1000 T/s, and a triangular wave), f = 125 Hz, or 1 T and 250 Hz
- It is interesting to note that this is more or less the range of fields and frequencies of interest for conductors for electric aircraft propulsion motors (0.5-2 T, 200-400 Hz)

Two Options: Superferric and Coil dominated

Superferric Design



Record Fast 290 T/s Accelerator HTS-based Magnet Tests

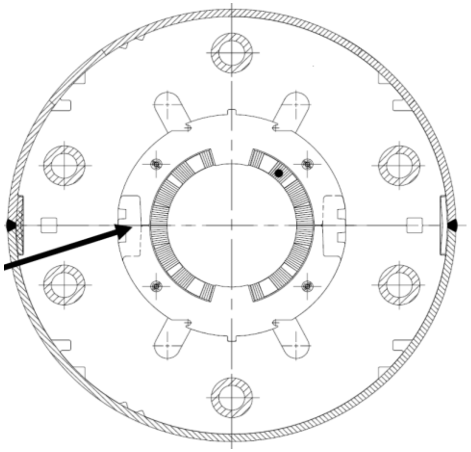
Henryk Piekarz, Steve Hays, Brad Claypool, Matt Kuffer, Vladimir Shiltsev (Fermilab)

Advantage:

Superferric minimizes SC (thus SC losses)

Can be designed with warm iron

Coil dominated Designs



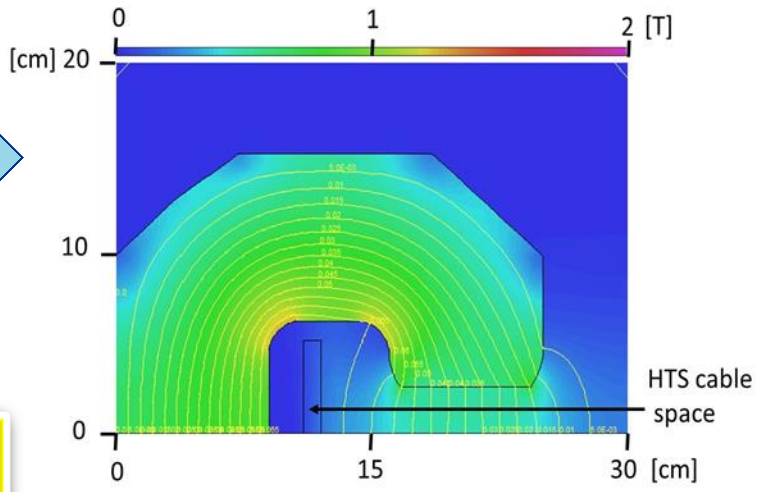
SIS-200/300 Nuclear physics fast ramp dipole, e.g., 4 T

Advantage: Higher fields, > 2T

Superferric REBCO Designs

- Piekarz et al., “New HTS fast ramping magnet technology”, NIM A, Vol 943, 2019, 162490.
- H. Piekarz, J. Blowers, S. Hays and V. Shiltsev, "Design, Construction, and Test Arrangement of a Fast-Cycling HTS Accelerator Magnet," in IEEE Transactions on Applied Superconductivity, vol. 24, no. 3, pp. 1-4, June 2014, Art no. 4001404, doi: 10.1109/TASC.2013.2285093
- H. Piekarz, “A Preliminary Consideration of Superconducting Rapid-Cycling Magnets for Muon Acceleration,” FERMILB-TM-2575-APC.

Basic Idea – Flat tapes generating field, low field at tapes



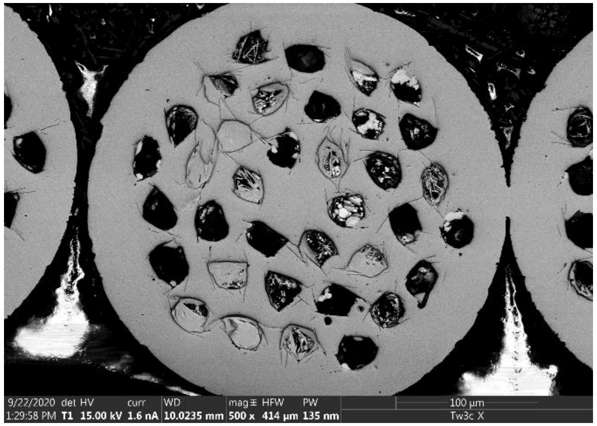
Here we explore conventional fine filament conductors for this application, and compare

METHOD USED

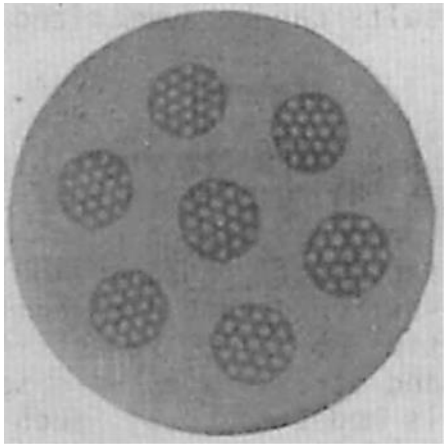
- Compares losses in conductors at 2 T sweep, 1000 T/s and 1 T sweep, 1000 T/s (125 and 250 Hz)
- Assumes full field on conductors
- Compares J_e and losses
- Includes conductor metrics
- Materials Considered: NbTi (not shown), MgB2, Bi2212, Al Hyperconductor
- Subsequent comparisons will be made with REBCO in tape and cable form

Various Low loss SC and Cryo-conductor Options

114-filament low AC-loss MgB_2
(with CuNi matrix)



Bi2212 Conductor from SMS (Otto)



Hyperconductor – High Purity Al
in Al-Fe-Ce matrix

Cu-coated Al Litz wire

Loss Components of a SC

Total loss

$$P_t = P_h + P_e + P_c + P_I + P_x$$

Hysteretic Loss

$$Q = (8/3\pi)B_0 J_c d \qquad P = Qf$$

Coupling loss

$$Q_{coup} = \frac{B_0^2 f L_p^2}{2\rho}\frac{1}{(1+\omega^2\tau^2)} \qquad \tau = \left(\frac{\mu_0}{2\rho_\perp}\right)\left(\frac{L_p}{2\pi}\right)^2$$

Eddy Current loss

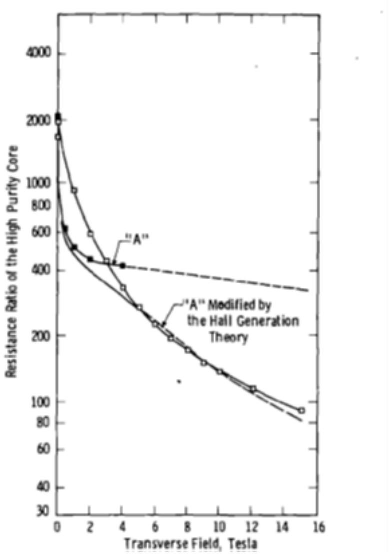
$$P_e = \frac{\pi^2}{k\rho_n}[(\mu_0 H_0)wf]^2$$

Transport Current loss

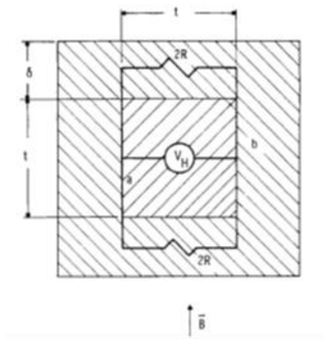
$$\frac{P}{L} = \frac{\mu_0 f}{\pi} I_c^2 \left[\left(1-\frac{I_0}{I_c}\right)\ln\left(1-\frac{I_0}{I_c}\right)+\frac{I_0}{I_c}-\frac{1}{2}\left(\frac{I_0}{I_c}\right)^2\right]$$

Because of large L_p/d ratio, and also f^2 like dependence, coupling loss dominates at high frequency

Anomalous Magnetoresistance in Hyperconductor composites



RRR vs *B* for (i) bulk HPAL – filled squares and extending dashed line, (ii) theory for Al composite including anomalous hall effect – solid line no symbols, and (iii) experimental data for composite with Al-Fe-Ce matrix, from Eckels [P.W. Eckles, N.C. Iyer, A. Patterson, A.T. Male, J.H. Parker, and J.W. Coltman, "Magnetoresistance; the Hall Effect in Composite Aluminum Conductors", Cryogenics 29 (1989) 749.]



$$V_h = R_h IBt/A$$

$$\rho_{TOT} = \rho_{bulk} + \rho_H$$

$$\rho_H = 2(R_H B)^2 \frac{\delta t}{A_a \rho_b}$$

"pseudo" resistanc
e

- Since this component scales as $1/\rho_{b,}$ we can choose, for example, Cu-10 Ni, with a resistivity of ≅ 10 μΩcm (roughly temperature independent).
- If we used such a material, then the anomalous magnetoresistance component would be hugely suppressed, and ignorable in fields below 14 T.

Je and Loss comparisons

25 Hz only, and 2 T sweep

Conductor	J_e (A/mm^2) 2 T, T_{op}	T_{op}, K	OD/d_f/L_p, mm/µm/mm	Ohmic, W/cm^3	Hyst, W/cm^3	Coup, W/cm^3	Eddy, W/cm^3	Transport, W/cm^3	Total	W/cm^3*(J_{cNbTi}/$J_{c'}$)
NbTi	2100	4.2	0.8/0.5/5	0	0.178	1	0.033	2.20	3.41	3.41
MgB_2	315	20	0.8/20/5	0	0.4	1	0.033	0.228	1.66	11.1
SMS Bi2212	500	20	0.3/20/10	0	0.433	.46	.0157	.131	1.04	4.37
HPAL Multi/braid	134	20	0.8/20/--	1	--	--		--	1	15.7
YBCO**	1620	20	2/2000/10	0						

** Tape stack

Benefit to higher temp operation, but only geometry that makes sense it very thin tapes or thin tapes/cables with superferric design

Summary

- Regimes for various superconductors and cryo-conductors for use in Fast ramp dipoles were reviewed
- Loss expressions for superconductors were calculated below the skin depth regimes
- Losses were compared between a low-loss NbTi strand and that of MgB2, Bi2212, Cryo-Al
- YBCO tapes with Parallel Field arrangement leads to lower loss, but computation of exact losses require details of orientation and field distribution
- Next step will be to compare losses of REBCO parallel in Superferric and non-superferric designs