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GENERALIZED MULTIDIMENSIONAL PROPAGATION
VELOCITY EQUATIONS FOR POOL-BOILING SUPERCONDUCTING WINDINGS

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GENERALIZED MULTIDIMENSIONAL PROPAGATION VELOCITY
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ABSTRACT

Several finite difference, finite element detailed analyses of propagation velocities in up to three dimensions in pool-boiling windings have been conducted for different electromagnetic and cryogenic environments. Likewise, a few full scale simulated winding and magnet tests have measured propagation velocities. These velocity data have been correlated in terms of winding thermophysical parameters. This analysis expresses longitudinal and transverse propagation velocities in the form of power function regression equations for a wide variety of windings and electromagnetic and thermohydraulic environments. The generalized velocity equations are considered applicable to well-ventilated, monolithic conductor windings. These design equations are used piecewise in a gross finite difference mode as functions of field to predict the rate of normal zone growth during quench conditions. A further check of the validity of these predictions is available through total predicted quench durations correlated with actual quench durations of large magnets.

INTRODUCTION

In several facets of pool-boiling LHe superconducting magnet design and analysis, it is necessary to predict how normal zones grow in the realistic thermohydraulic environments of the magnets. This capability has evolved over the years by first making one-dimensional propagation predictions in limiting environments by closed form or finite difference predictions.^{1,2} Limited propagation measurements have been made in model magnets and full-scale model winding tests.^{3,4,5} Very limited measurements have been made in the real environments of full-size large magnets where events have been imposed to perpetrate a quench.^{6,7} Some of the model winding tests and large magnet quench tests have contributed an understanding of the thermohydraulic and hydrodynamic responses and environment in the windings.^{5,7}

Finally, detailed two- and three-dimensional propagational predictions have been made by finite difference models where quench thermohydraulic environments have been assumed that simulate the few large magnet quench responses.⁸ The three-dimensional finite element analyses can be made to fit the actual magnet propagations by straightforward adjustments of the thermohydraulic and energy transport assumptions, thereby lending credence to the simulation techniques. It then is reasonable to correlate all these test and simulation data simultaneously by regression equations based on a unified theory and selected thermophysical/thermohydraulic parameters for the windings. This has been done and the rather sparse data correlated by propagation velocity equations in three orthogonal directions.

The practical validity of the equations is the good comparison between predicted total time to drive the entire winding normal during a quench and the times actually experienced in large magnet quenches.^{7,9}

SIMULATION AND TEST DATA

Test data on longitudinal propagation velocity of full-scale conductors in a superconducting magnet winding is limited.^{5,6} Transverse propagation data is even more limited because it is necessary to separate the longitudinal velocity influence of the turns from the transverse energy transport and

propagation velocity between turns, layers, and/or pancakes. Furthermore, isolation of the thermohydraulic/hydrodynamic contributions of the helium to the propagation phenomenon requires even greater care and expense in testing.⁵

Our approach in cryostability and quench prediction has been to develop one-, two-, and three-dimensional finite difference model simulation analyses. Thermohydraulically sound assumptions of the helium behavior and energy transport are made in concert with helium behavior we have visually seen and measured with temperature sensors in conductor/insulation bundle tests. The boundary conditions and assumptions are varied and surveyed until agreement has been achieved with observations in the few pertinent full-scale tests. The most elaborate of these analyses are the two- and three-dimensional analyses done for the Mirror Fusion Test Facility (MFTF) conductor.⁸ Yet, the cost of this simulation analysis is a small fraction of a full-scale magnet cryostability/quench test but is valid data in agreeing with the limited testing done to date. Therefore, the finite difference simulation data is treated similarly to test data. Since several MFTF magnets are mentioned by their acronyms, Figure 1 is an annotated schematic of the MFTF-B magnet set made up of large solenoid and C-shaped magnets.

Table 1 summarizes one-dimensional longitudinal propagation velocities from computer simulations and tests of various monolithic copper stabilized conductors for large superconducting magnets preceeding the MFTF-B magnets set. Nominal thermophysical, electrical, and magnetic properties affecting propagation are listed as well as selected typical references for the prediction technique and data.

Table 2 summarizes the propagation velocities predicted for the different MFTF-B magnets, different electromagnetic environments, and the different thermohydraulic environments considered for the conductors. These data are extracted directly from the detailed two- and three-dimensional thermal simulation analyses for the MFTF complex monolith conductor. Longitudinal velocity is in the Z direction. The real longitudinal velocity, i.e., the

Figure 1. MFTF-B Axicell Configuration Magnet System

Table 1. Summary of Dry Longitudinal Propagation Velocities
from Magnet Conductor Analyses and Tests

Magnet	Conductor Type	Current (Amps)	Current Density (Amp/cm ²)	Maximum Field (Tesla)	RRR	Cu/Sc Ratio	T _{BATH} (°K)	q (W/cm ²)	V _Z (m/s)	Reference
Elmo Bumpy Torus (EBT-P)	Small Monolith	1000	10000	8	75	3.0	4.2	0.576	3.40	Simulation
	Small Monolith	1500	15000	8	75	3.0	4.2	1.296	5.00	
Cask Magnet Prototype System (CMPS)	Medium Monolith	7400		8	110	12.43	4.2	0.255	5.42	Simulation
				7				0.234	4.15	
				6				0.209	3.15	
Stanford Super- Conducting Magnet (SSM)	Medium Monolith w/Cable Insert	5140		8	110	4.60	4.2	0.700	7.40	2
Large Coil (GDC-LCP)	Large Monolith w/Cable Insert	10300		8	110	13.60	4.2	0.210	5.00	1,
Yin-Yang (MFTF-A)	Complex Monolith	5775		7.68	200	6.20	4.2 test	0.190	6.82	6, test

Table 2. Summary of 2- and 3-Dimensional Propagation Analysis Results
(for Different Helium Thermohydraulic Environments)

MIRROR FUSION TEST FACILITY- B		CURRENT (Amps)	MAX FIELD (Tesla)	3D RUN	DRIED CONDUCTORS		INIT. NORM. COND.	2D RUN	DRIED CONDUCTORS		BOILING CONDUCTORS	
MAGNET	CONDUCTOR				V_z m/sec	V_z (adj)* m/sec	V_z m/sec		V_x cond/s	V_y cond/s	V_x cond/s	V_y cond/s
<u>DRY W/NO BOILING/NO FLOW</u>												
A-Cell	MFTF GI	5416	7.8	3D #9	5.1	6.375	4.3	2D #3	10.0	5.71		
A-Cell	"	5416	5.5	3D #10	2.8	3.50	1.9		4.0	2.94		
A20	"	5416	7.625	3D #11	4.9	6.125	3.6		7.19	4.38		
A20	"	4542	7.625	3D #12	3.85	4.81	2.75	2D #6	5.21	2.55		
A1	"	4392	7.625	3D #13	3.75	4.69	2.60	2D #5	5.0	2.45		
T1	"	5427	6.02	3D #15	3.20	4.00	1.95	2D #7	3.53	2.18		
T2	MFTF GII	5874	4.83	3D #14	5.80	7.25	4.35	2D #8 b	8.57	3.53		
<u>DRY W/NO BOILING/BUT FLOW</u>												
A-Cell	MFTF GI	5416	7.8					2D #2	17.14	10.0		
<u>BOILING/BUT NO FLOW</u>												
A-Cell	MFTF GI	5416	7.8	3D #3	5.0		3.0		10.00	6.53		
				3D #8	4.53		2.9		10.10	4.34		
		5416	5.5	3D #7	3.33		1.6		2.52			
									Avg 5.43			
<u>BOILING W/FLOW</u>												
A-Cell	MFTF GI	5416	7.8	3D #2	5.00		3.00		16.67	8.92		
				3D #6					14.04	8.94		
		5416	7.8					2D #1a	16.67	9.23	7.05	5.71
									Avg 15.79			
		5416	5.5	3D #16	Recovers in .095 sec							

* Finite element/finite difference longitudinal propagation velocity corrected by 1.25 factor for approach to differential limit per findings of simulation studies as function of finite element length survey.

ultimate velocity in the approach to the limit of the differential equations, has been estimated from the finite element/finite calculation interval result using a correction for one-centimeter long nodes indicated from early simulation analyses error studies. Transverse velocities are in the x-direction, considered parallel to the width dimension of the conductor, and in the y-direction parallel to the height dimension of the conductor. Since these analyses were for real magnets, the x-direction was also parallel to a layer on the inner ring or surface facing the central field of the magnet and the y-direction was in the build direction with field decreasing with progression away from the inner ring peak field region. This is the reason V_y is less than V_x .

DEVELOPMENT OF CORRELATION EQUATIONS FOR PROPAGATION VELOCITIES IN THREE DIMENSIONS

The objective and approach, while not mathematically elegant, is to start with available evidence and develop practical, easily applied, engineering predictions for propagation and normal zone growth rates in windings. Propagation velocity may be expressed in the form of power function regression equations which have been fit to the data of the indicated magnet conductor propagation simulation analyses and tests. A review of the parameters influencing heat flow and heat storage permits the rational assembly of the terms in the numerator or denominator, then powers are developed from slopes by piecewise logarithmic plotting of velocity against a parameter with the other terms constant, and finally the correlation constant is determined by a least-squares-fit. The logic guiding the developmental derivation of these regression equations for the dry propagation condition (no boiling, no flow) follow.

From recovery and propagation velocity prediction and test results on various magnets, general velocity of propagation at the normal front thermal gradient is expected to be a function of the general thermodynamic parameters.

$$V = f(\text{heat conduction, heat storage to normalize, intensity of normal heating}) \quad (1)$$

Converting this to a more specific statement for dry longitudinal velocity where there is little cooling heat removal.

$$V = C_z \frac{\text{Thermal Conductance}}{\text{Heat Capacity}} \frac{(\text{Joule Flux})^n}{\text{Temperature Margin} \left(\frac{B_{\text{ICDES}}}{B_{\text{sc}}} \right)^m} \quad (2)$$

Thermal conductance at low temperature is expected to enter as approximately the first power and may be considered to be proportional to $\frac{RRR}{B} A_{\text{cu}}$.

Heat capacity is expected to enter the denominator as the first power and may be shown to be $A_{\text{cu}} C_{\text{cu}} \left(\frac{R + \frac{C_{\text{sc}}}{R}}{\frac{C_{\text{cu}}}{R}} \right)$ where the thermophysical parameters are the means between bath temperature and critical temperature.

Temperature margin may be stated as a linear function of the difference between critical temperature and bath temperature which for NbTi is $(9.09 - 0.439B - T_B)$.

Joule flux at low temperature, but full normalization, is simply a way of stating the intensity of volumetric heat deposition.

$$\frac{B_{\text{ICDES}}}{B_{\text{sc}}} \text{ is a measure of the intensity of}$$

exercising the full field capability of the superconductor.

The exponents are placed on the more easily defined terms but empirically adjust for non-linearities in other terms.

Critical temperature for NbTi is:

$$T_c = 9.09 - 0.439B, \text{ K} \quad (3)$$

where: B = field in tesla.

Copper heat capacity over the range of temperatures of interest in normalization and propagation may be expressed as:

$$c_{cu} = K_c T_m^{2.5} \quad (4)$$

where: c_{cu} = specific heat capacity of copper ($\text{mJ}/\text{cm}^3 \cdot ^\circ\text{K}$)

K_c = constant

T_m = mean temperature between LHe bath temperature (T_B) and critical temperature, ($^\circ\text{K}$)

For NbTi:

$$T_m = \frac{9.09 - 0.4398T_B}{2} \quad (5)$$

where: T_B = liquid helium bath temperature, ($^\circ\text{K}$)

K_c is evaluated to be 0.025.

A term in the velocity equation makes an adjustment for the much higher heat capacity of the NbTi superconductor by the relationships of conductor copper: superconductor ratio, R, and the ratio of c_{sc}/c_{cu} . the superconductor heat capacity, in this case for NbTi, is a function of field over the temperature range of interest.

After manipulation and introduction of the foregoing developed terms the longitudinal velocity equation becomes:

$$v_z = c_z \left(\frac{B_{sc}}{B_{IcDes}} \right)^m \left[\frac{1}{0.025 \left(\frac{9.09 - 0.4398T_B}{2} \right)^{2.5}} \right] \left[\frac{RRR}{B} \left(\frac{R}{R + \frac{c_{sc}}{c_{cu}}} \right) \right]^x \left[\frac{1}{9.09 - 0.4398 - T_B} \right] q^n \quad (6)$$

where the constant C_z and unknown exponents m, n may be evaluated by curve fitting the finite element predicted and measured velocity data for the various conductors.

For transverse velocity the basic velocity relationship to the thermophysical parameters is similar to equation (2). However, now the controlling transient thermal conductance is that of the interconductor insulation and is also inversely proportional to the insulation capacitance or overall is proportional to $A_{ins} K_{ins} / t^2$. The heat capacity of the conductor and superconductor is $(A_{cu} + A_{sc}) c_{cu} \left(R + \frac{c_{sc}}{c_{cu}} \right) \left(\frac{R + \frac{c_{sc}}{c_{cu}}}{1+R} \right)$.

After manipulation, the transverse velocity equation becomes:

$$V_x = C_x \left(\frac{B_{sc}}{B_{IcDES}} \right)^m \left[\frac{1}{0.025 \left(\frac{9.09 - 0.439B + T_B}{2} \right)^{2.5}} \right] \frac{K_{ins}}{t_x} \left(\frac{H_x}{H_x \cdot W_y} \right) x$$

or y or y

$$\left(\frac{1+R}{R + \frac{c_{sc}}{c_{cu}}} \right) \left[\frac{1}{9.09 - 0.439B - T_B} \right] q^n \quad (7)$$

where the constant unknown exponents may be evaluated by curve fitting the finite element predicted data.

Piecewise log-log plotting of selected velocity data of Tables 1 and 2 versus joule heat flux or B_{sc}/B_{IcDES} for the limited conditions where all the rest of the parameters in the equations are similar yield the exponents n and m as slopes on the log-log plots. For V_z , $n = 0.67$, $m = 1.0$. For V_x or y , $n = 1.63$, $m = 2.0$. With all the terms evaluated except the constants of proportionality, C_z , C_x or y , the equations are solved for each case to evaluate the constant of proportionality. These are listed in Table 3 for C_z and averaged yielding average $C_z = 305$ for velocity in cm/sec with maximum dispersion of 13 percent.

Table 3. Determination of Longitudinal Velocity Equation Constant

Magnet-Conductor	Operating Parameters		C_z
	Current (Amp)	Field (Tesla)	
EBT-P	1000	8	310
	1500	8	263
CMPS	7400	8	275
SSM	5140	8	306
LCP	10300	8	282
MFTF-A	5775	7.68	291
A-Cell - GI	5416	7.80	307
	5416	5.50	326
A20 - GI	5416	7.63	312
	4542	7.63	311
A1 - GI	4392	7.63	317
T1 - GI	5427	6.02	339
T2 - GII	5874	4.83	323
Mean			305
Dispersions			+34
			-42

The propagation velocity in both transverse directions can be accommodated with one constant even though the insulations are different. The list in Table 4 shows the individual constants with MFTF conductor for insulation conductivity in W/cm-°K and the aggregate C_x or $y = 15300$ for transverse velocity in terms of conductors normalized per second with maximum dispersion of about 18 percent.

Table 4. Determination of Transverse Velocity Equation Constant

Magnet-Conductor	Operating Parameters		C _x	C _y
	Current (amp)	Field (tesla)		
A-Cell - GI	5416	7.8	14804	16035
A20 - GI	4542	7.63	15360	14260
A1 - GI	4392	7.63	16350	15197
T1 - GI	5427	6.02	14845	17389
T2 - GI	5874	4.83	15886	12490
Directional Mean			15449	15074
Combined Mean			15261	
Dispersions			+2128	
			-2771	

The dry (no boiling, no flow) propagation velocity equations applicable to a general pool-boiling, monolithic conductor winding pack are now fully described and restated. The equations, being empirical, have dimensional terms and constants, so the dimensions of the parameters are defined and must be carefully used.

Longitudinal velocity along conductor (cm/sec):

$$v_z = 305 \left(\frac{B_{sc}}{B_{IcDES}} \right) \left[\frac{1}{0.025 \left(\frac{9.09 - .439B + T_B}{2} \right)^{2.5}} \right] \left[\frac{RRR}{B} \left(\frac{R}{R + \frac{C_{sc}}{C_{cu}}} \right) \right]^x$$

$$\left[\frac{1}{9.09 - 0.439B - T_B} \right] q^{0.67} \quad (8)$$

Velocity transverse to conductor in x or y direction (conductors/sec):

$$V_{x \text{ or } y} = 15300 \left(\frac{B_{sc}}{B_{IcDES}} \right)^2 \left[\frac{1}{0.025 \left(\frac{9.09 - 0.439B + T_B}{2} \right)^{2.5}} \right] \frac{K_{ins}}{t_{dry}^2} \left(\frac{H_{or} W_y}{H_x \cdot W_y} \right) \times$$

$$\left(\frac{1+R}{R + \frac{c_{sc}}{c_{cu}}} \right) \left[\frac{1}{9.09 - 0.439B - T_B} \right] q^{1.63} \quad (9)$$

The parameters of the equations have the following definitions:

- V_z = dry propagation velocity, cm/sec
- B = local magnetic field, tesla
- T_B = liquid helium bath temperature, K
- q = joule heat flux, w/cm^2
- c_{sc} = mean heat capacity of superconductor from bath temperature to superconductor critical temperature considering the field-thermodynamic effect on heat capacity, $joule/cm^3K$
- c_{cu} = mean heat capacity of copper from bath temperature to local superconductor critical temperature, $joule/cm^3K$
- RRR = residual resistivity ratio of copper, dimensionless.
- R = copper/superconductor volume ratio, dimensionless
- $V_{x \text{ or } y}$ = transverse dry propagation velocity in x or y directions, conductors per second
- t_{dry} = insulation thickness in x or y direction, cm
- H_x = height of conductor normal to x direction, cm
- W_y = width of conductor normal to y direction, cm

B_{sc} = maximum field that superconductor will service at bath temperature, ~ 8.3 tesla for NbTi.

B_{IcDES} = maximum field that conductor under consideration is designed for based on critical current margin; ~ 8.3 tesla for MFTF Grade I, ~ 5.2 tesla for MFTF Grade II.

K_{ins} = insulation conductivity for temperature range between T_B & T_{CRIT} , $\frac{W}{cm \cdot ^\circ K}$.

These dry propagation equations are applicable to a general pool-boiling, monolithic conductor winding pack with NbTi superconductor. The results of the above equations for dry propagation velocity can be modified for other hydrodynamic environments. Simple multipliers for other hydrodynamic environments derived from the detailed results of Table 2 may be applied to the dry propagation velocity equations for alternative conditions as described below:

- 1) Equations used directly where liquid is assumed blown away but then not experiencing vapor flow (instantaneously dry conductor).
- 2) For conductors with boiling around them until liquid is gone.
 - a) Multiply Equation (8) V_z by 0.6 at 7.8 tesla and 0.48 at 5.5 tesla with linear variation between and beyond these points.
 - b) Multiply Equation (9) for V_x by 0.45 and for V_y by 0.62.
- 3) For conductors with liquid blown away but receiving vapor flow from boiling somewhere else in system, multiply Equation (9) V_x or V_y by 1.57. Equation (8) V_z is not increased significantly or uniformly.

The above dry propagation velocity equations are specifically for NbTi conductor parameters. These equations may be modified for applicability to Nb_3Sn monolithic copper stabilized conductors by changing the expression for critical temperature, difference between critical temperature and bath

temperature, mean temperature between LHe bath temperature and critical temperature, mean heat capacity of Nb_3Sn superconductor with field effect for the temperature range from bath to critical temperature, and maximum field for practical Nb_3Sn service (14.0 tesla) and maximum design field for specific superconductor.

APPLICATIONS OF PROPAGATION EQUATIONS

The equations may be used in any large magnet to predict propagation velocity at any specific field location and to compare with actual propagations in large magnets. The initiation of the propagation in an inherently cryostable pool-boiling magnet at its design operating conditions may be the result of different fault scenarios. Some of these during magnet operation might be or have been by:

- 1) Heaters in the windings for testing performance^{3,4,6}.
- 2) Sufficiently rapid dump to cause normalization by inductive effects⁷.
- 3) Simply increasing current until significant current sharing occurs and sections of turns become normal.
- 4) Outright failures where vacuum vessel breach occurs, liquid level drops in the magnet exposing significant sections of winding, or sufficiently high heat sources such as neutron heating, plasma disruption, or stick-slip friction cause massive vapor evolution beyond the vapor clearing capability of the windings and plenums.

From the type of propagation and quench initiating event and knowledge of the winding and plenum space hydrodynamic and ventilation configuration, a rather gross internal helium behavior and environment condition may be postulated. In response to the particular environment, the propagation velocity equations are used piecewise as a function of the field map of the winding to predict the rate of normal zone growth in the winding during quench.

Temperature rise of sections of the winding as the normal zone grows are predicted piecewise in a gross finite difference mode, as each given block of conductor normalizes. The progressive temperature rise of blocks of the winding as major blocks of conductor progressively normalize is estimated by correcting conservative adiabatic temperature rise predictions from a program such as SUPERQ.² The corrections range from 20K decrement from maximum temperature to rises only 65 percent of adiabatic temperature rise predictions depending on helium behavior and environment.⁸ The block-wise temperature rise increases resistivity in each block and permits prediction of joule heat dissipation, I^2R , in each block of normal conductors, as a function of time, using the appropriate current, I , at that time if I is changing, such as with a dump and the value of resistance for the block $\rho \frac{L}{A_{cu}}$ where ρ = copper stabilizer resistivity at that time (temperature), L = length of conductor in that block, and A_{cu} = conductor copper stabilizer cross-section area. The total heating in the winding is the aggregate heat from each of the blocks that have normalized by each successive time step.

Figure 2 shows the resulting joule heat rate histories from start of normalization for two typical MFTF magnets assuming dry propagation. The Barrier magnets are characterized by field approaching 8 tesla and moderate current while the Transition magnet operates at higher current but lower, 5 tesla, maximum field. These relationships combine with the geometry differences of the two types of magnets to result in full normalization of the windings in exactly 10 seconds and before current dump starts. The continuing increase in joule heating is due to the resistivity of the winding rising with temperature faster than I^2 drops with the dump. Finally, at 35 to 40 seconds the lowering of I^2 begins to dominate and joule heat rate begins to decay.

These predicted times of full normalization and peak joule heating compare favorably with the respective phasing of these events, about 15 and 25 seconds on the Japanese large coil⁷. Baseball magnet took 10 to 30 seconds for full quench of the winding⁹. Therefore, the dry conductor assumption and application of the equations is conservatively severe.

Application of the multiplying factors for a "wetter helium environment" ranging from 0.45 to 0.60 to the dry propagation velocities easily prolongs the total normalization time to those experienced on the Japanese large coil and the Baseball magnet.

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