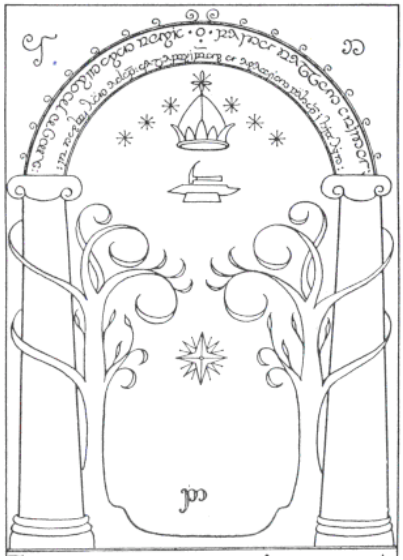
GANDALF

A computer code for quench analysis
of dual flow CICC's

Version 2.2

by CryoSoft

January 2001



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Gandalf ! If you had heard only a quarter of what I have heard about him, and I have only heard very little of all there is to hear, you would be prepared for any sort of remarkable tale.

(J.R.R.Tolkien, The Hobbit)

Introduction

GANDALF is the numerical implementation of a 1-D model for the simulation of quench initiation and quench propagation in CICC's with cooling channels. The model is described extensively in Refs. [1,2], together with the details on the numerical method (see also [3] and [4]). The basic conductor scheme modelled is reported in Fig. 1. The 1-D model consists of a maximum of four independent components at different thermodynamic states:

- the strands, consisting of stabilizer and superconductor,
- the conduit, grouping the jacket and insulation,
- the *bundle* helium, surrounding the strands in the cable, and
- the *hole* helium, flowing in an independent cooling passage.

The temperatures of these four components are treated separately and the energy balances are coupled through heat transfer coefficients at the contact (wetted) surfaces. With respect to the helium flow, Gandalf can treat single phase supercritical and superfluid compressible helium flow. The model takes into account the presence of two separate flows at different thermodynamic state (i.e. pressure and temperature) and velocity. The two flows are assumed to take place in the intersticial spaces of the cable bundle (as for standard CICC's) and in a separate cooling hole. The helium in the bundle and in the hole exchange mass and momentum in addition to energy. Note that it is possible, by setting the hole area to zero, to suppress the hole flow and to solve a simplified model for a CICC without central cooling hole. In this case Gandalf effectively eliminates the equations that are not necessary, thus avoiding unnecessary CPU and memory overheads.

The conductor length, or flow path, is modelled along its length using linear finite elements. At each node 8 degrees of freedom are defined, i.e. the temperature of strands and conduit, and the two temperatures, pressures and velocities of the bundle and hole helium. A schematic view of the finite element is given in Fig. 2, where the thermal couplings are evidenced and the dof's are indicated.

The boundary conditions at the ends of the flow paths are assumed to be given for the helium either by reservoirs with specified pressure and temperature or by closed valves (i.e. no flow). The conductor ends are assumed adiabatic. In case of helium superfluid the boundary temperature is prescribed.

Operating current and magnetic field can be arbitrarely specified as a function of time and position (for the field)

An external heat source in the strands or in the conduit, user's specified, initiates the quench. The Joule heat generation is computed consistently with the non-linear critical current density relation. The electric field in the superconductor at the resistive transition is modelled using a power law dependence, which can be reduced to the limit of infinitely sharp transition. The Joule heat is distributed resistively among strands and conduit (this feature is useful for low-resistance conduits such as, e.g., Aluminium).

Additional features of the numerical implementation of *GANDALF* are automatic mesh size and time step adaptivity. The mesh is refined or coarsened among a minimum and a maximum element size

specified by the user following the evolution of the normal fronts in the flow path, by means of a front tracking procedure. The time step is adapted in order to satisfy an *a priori* relative accuracy criterion based on a simplified model equation and the amplificaton factor of the time integration scheme. At the moment two options (to be selected by the user) are programmed for the integration method: a second order accurate algorithm for higher accuracy but subject to the possibility of oscillations in the solution, and a first order algorithm which damps the oscillations, with a higher numerical stability, but lower accuracy. Details on the numerics are again given in [1].

The present version of *GANDALF* computes some error and quality indicators for the solution obtained. They are based on variables interpolation, numerical diffusivity and additional numerical propagation. The user must use this information to check that the solution is numerically converged. In other words, the trade-off between CPU cost and solution quality is left to the user. Later we deal with the meaning of the error and quality indicators and we give guidelines for judging the quality of a solution.

The solver decides whether a quench or a recovery has taken place. In particular, the algorithm for the decision is based on the total Joule heating in the conductor length analysed. The decision is taken at the last step in the following way:

```
if (time ≤ 2 * heating_time  or d( Joule_heating)/dt < 0) then
      transient in process
elseif(time > 2*heating_time and Joule_heating = 0) then
      recovery
elseif(time > 2*heating_time and Joule_heating > 0) then
      quench
endif
```

This insures that no decision on recovery and quench is taken before the heating is off, and until the joule heating is growing. Note that, as explained in the description of the input parameters, the heating time TAUQ is used for the tests above. This implies that, in the case that the user defines the heating through an external routine, the value of the heating time must still be set if a meaningful decision on recovery/quench is desired. A message is output at the end of the run in the log file, indicating the event that has been recognized based on the decision-taking procedure given above. The possible events are:

```
      "Transient still in process"
      "The conductor has recovered"
      "The conductor is quenching"
```

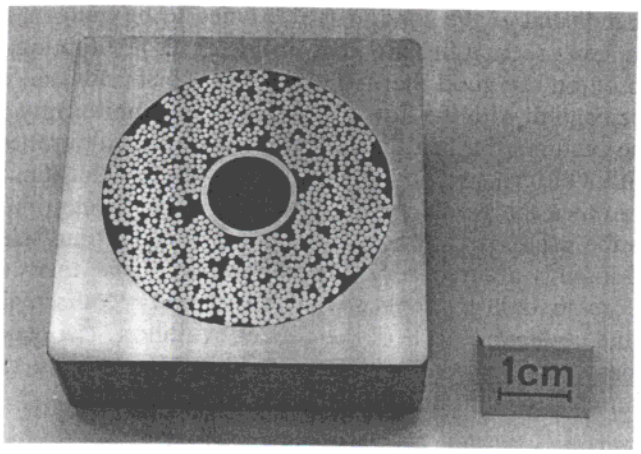

Figure 1. Typical geometry of a CICC with central cooling hole as modelled in *GANDALF*.

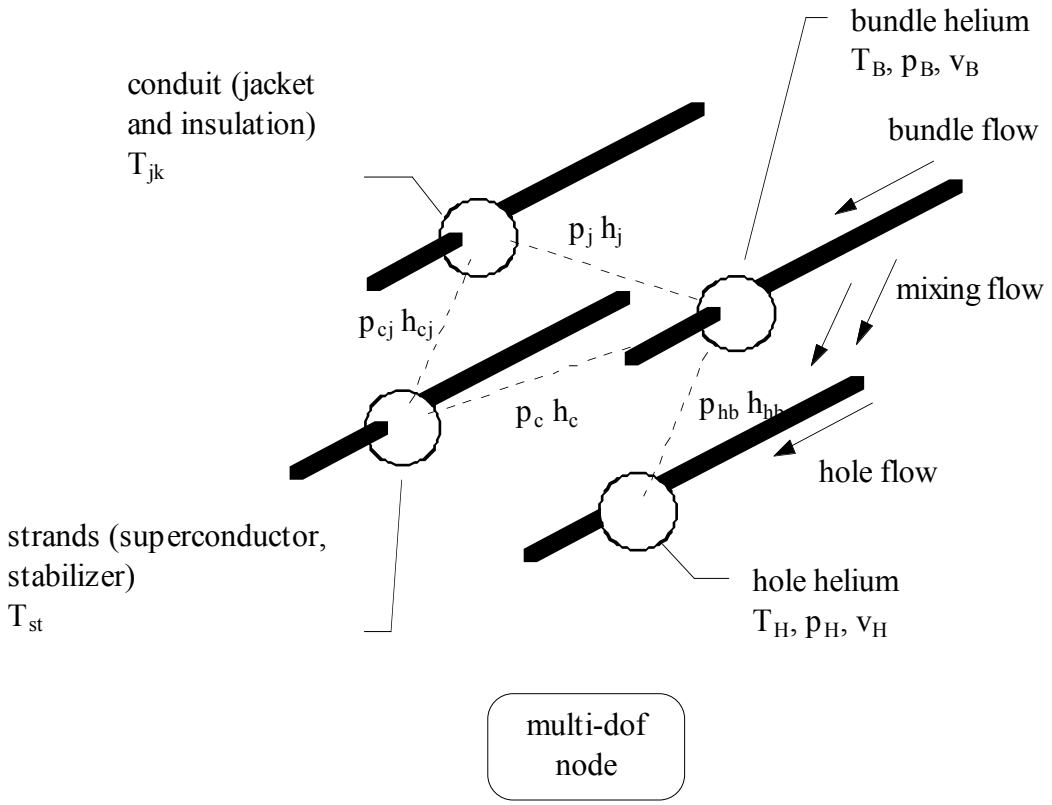

Figure 2. Basic finite element used in *GANDALF*, showing the degrees of freedom and the thermal and flow coupling among components.

Code Structure

Main solver

This is the portion performing the calculation and generating the results. The code performs input and output on the following units

File Name	Usage
input file	Input of the data for the run
`gandalf.store`	Storage for restart and post-processing
`gandalf.output`	Output of the results

Units 5 and 6 are attached to the terminal and are used for debugging or monitoring purposes. Gandalf requires a single interactive input, the file name where the input data is located. The results are output in ASCII format and as binary storage, this last is used either for restarts (recovering the results up to the last time stored) or for post-processing (see later for a description).

Note: FORTRAN unit numbers above 50 are reserved for internal use

Post processor

After a run it is possible to plot or print tables of the results stored on the binary file `gandalf.store` using the dedicated post-processor. The post-processor reads the binary data and a sequence of commands. Each command is executed in sequence and causes the generation of PostScript plots or tables of selected data. The post-processor performs input and output on the following units

File Name	Usage
`gandalf.store`	Data stored, read-in for post-processing
command file	ASCII sequence of commands determining the generation of plots or tables. The commands are read sequentially and executed
`g1dp.tables`	ASCII file with table of results, generated by the post-processor following the commands read from *command.file*
`PostScript.ps`	Plots in PostScript format, generated by the post-processor following the commands read from *command.file*

Units 5 and 6 are attached to the terminal and are used for debugging or monitoring purposes.

Note: FORTRAN unit numbers above 50 are reserved for internal use

Material properties

The main solver needs to be linked to a set of routines for the calculation of the material properties of solid materials and helium. As these routines are at the lowest level in the code execution, their efficiency is of paramount importance. A set of routines is provided by default with the program. These can be easily changed provided that the calling arguments are respected (and obviously units !) and keeping in mind the requirements on the code efficiency. For the complete list of the property functions, please refer to the manuals of the libraries Solid and He_table of CryoSoft.

Input Variables

The following table contains the input variables, their physical dimensions, default value and meaning for the *GANDALF* processor. The input of GANDALF is done using the FORTRAN instruction `NAMELIST`. The namelist is called `INDATA`. A sample input file is reported in the end of the manual. Note the first line in the input file, read-in as the problem title.

Conductor cross section composition and properties

Variable	Type	Units	Default	Meaning
ICBFUN	I	(-)	0	Flag used to set the geometry of the cable cross section as a function of position along the length (-1) user's defined through external function EXTCAB to be linked with the code (0) constant, as specified through input
ASC	R	(m^2)	0.0	Superconductor cross section
AST	R	(m^2)	0.0	Stabilizer cross section
AJK	R	(m^2)	0.0	Jacket (conduit) cross section
AIN	R	(m^2)	0.0	Insulation cross section
ISC	I	(-)	0	Flag used to define the superconductor type: (<0) user's defined. In this case all thermophysical and electrical properties are provided through external functions UserDensity, UserSpecificHeat, UserConductivity, UserCurrentSharing, UserCriticalTemperature and UserCriticalCurrent to be linked with the code (0) None (31) standard NbTi (32) standard Nb3Sn
IST	I	(-)	0	Flag used to define the stabilizer material: (<0) user's defined. In this case all thermophysical and electrical properties are provided through external functions UserDensity, UserSpecificHeat, UserConductivity and UserResistivity to be linked with the code (1) Copper (2) Aluminium
IJK	I	(-)	0	Flag used to define the jacket material:

				(<0) user's defined. In this case all thermophysical and electrical properties are provided through external functions UserDensity, UserSpecificHeat, UserConductivity and UserResistivity to be linked with the code (1) Copper (2) Aluminium (3) Titanium (11) Copper-Nickel (13) Stainless Steel (14) Inconel (15) Incoloy 908
IIN	I	(-)	0	Flag used to define the insulating material: (<0) user's defined. In this case all thermophysical properties are provided through external functions UserDensity, UserSpecificHeat and UserConductivity to be linked with the code. (21) Epoxy Resin (22) Glass-Epoxy (23) Polyimide (Kapton)
EPSLON	R	(-)	0.0	Total longitudinal strain in the superconductor in operating condition. Strain is assumed constant during the transient
E0	R	(V/m)	0.0	Electric field criterion for the definition of the resistive transition at the critical current. E0 is needed if the user chooses to model the electric field E in the superconductior by the power law: $E = E_0 \left(\frac{I}{I_c}\right)^n$, where I is the current in the superconductor and I_c is the critical current. This model is used for a choice of NPOWER below 250 (see below).
NPOWER	I	(-)	0	Exponent of the power-law used to model the longitudinal electric field in the superconductor (see above). The power law is used only for values of 0 < NPOWER ≤ 250. For NPOWER > 250 a sharp transition is assumed (zero resistance below I_c, infinite resistance above I_c), which does not require the definition of E0.
RRR	R	(-)	0.0	Residual resistivity ratio for stabilizer material
ICHFUN	I	(-)	0	Flag used to set the geometry of the helium channels as a function of position along the length

				(-1) user's defined through external function EXTCHN, to be linked with the code. (0) constant
AHEB	R	(m^2)	0.0	Helium cross section in the *bundle* channel. This channel usually represents the helium flow in the intersticial space among the strands.
AHEH	R	(m^2)	0.0	Helium cross section in the *hole* channel. This channel usually represents a low impedance cooling path in the cable. This cross section can be set to 0.0 to eliminate the double flow features. In this case the *GANDALF* model is identical to that for a single flow channel CICC
DHB	R	(m)	0.0	Hydraulic diameter of the *bundle* channel (used only for the calculation of the frictional pressure drop and of the Reynolds number). This variable is usually set as four times the ratio of the cross section of the *bundle* channel A_{HeB} to its wetted perimeter p_B, i.e. $D_{hB} = 4\frac{A_{HeB}}{p_B}$
DHH	R	(m)	0.0	Hydraulic diameter of the *hole* channel (used only for the calculation of the frictional pressure drop and of the Reynolds number). This variable is usually set as four times the ratio of the cross section of the *bundle* channel A_{HeH} to its wetted perimeter p_H, i.e. $D_{hH} = 4\frac{A_{HeH}}{p_H}$. This variable is not used in the case AHEH=0.0 (i.e. for a single flow model)
PHTC	R	(m)	0.0	Perimeter used for heat transfer calculation among the strands and the *bundle* helium channel. This perimeter is usually a fraction (e.g. 5/6) of the total wetted perimeter p_B of the strands in the conductor. The correction factor takes into account that the wetted surface can be reduced in a compated conductor. The heat transfer coefficient used over this perimeter is computed by the routine EXTHCB
PHTCJ	R	(m)	0.0	Perimeter used for heat transfer calculation between the conductor strands and the jacket. Although the heat transfer between the strands and the jacket is more likely to be governed by the contact heat resistance, it is treated as a convective heat transfer with *wetted* perimeter PHTCJ between the two components. The heat transfer coefficient used over

				this perimeter is computed by the routine EXTHCJ
PHTJ	R	(m)	0.0	Perimeter used for heat transfer calculation between the jacket and the *bundle* helium channel. The heat transfer coefficient used over this perimeter is computed by the routine EXTHJB
PHTHB	R	(m)	0.0	Perimeter used for heat transfer calculation between the *bundle* and the *hole* helium channels. This perimeter is typically the physical perimeter of the pipe wall separating the two flows. In the case of absence of physical wall the perimeter PHTHB is an imaginary boundary that separates the two parallel channels. The heat transfer coefficient used over this perimeter is computed by the routine EXTHHB
PERFOR	R	(-)	0.0	Percentage perforation of the separation perimeter between the *bundle* and *hole* helium channels PHTHB. This factor, between 0 and 1, describes the transverse permeability of the hole-bundle interface. A value of 1 implies that the whole perimeter PHTHB is transparent to transverse flow (i.e. no physical wall), a value of 0 means no transverse flow (i.e. a continuous physical wall).

Operating current

Variable	Type	Units	Default	Meaning
IOP0	R	(A)	0.0	Initial operating current in the coil
IOPFUN	I	(-)	0	Flag used to specify the behaviour of the operating current in time: (-1) user's defined. through external function EXTI to be linked with the code (0) constant in time (1) exponential decay with time constant TAUDUM after a delay TAUDET
TAUDET	R	(s)	0.0	If IOPFUN=1 determines the delay between initiation of the transient anmd the sitching action to dump the coil. The current is constant for 0 < t < TAUDET
TAUDUM	R	(s)	0.0	In the case IOPFUN=1 determines the time constant of the dump of the current (starting after TAUDET seconds with exponential law in time). For t > TAUDET the current is given by: IOP = IOP0 * exp((t-TAUDET)/TAUDUM)

Operating magnetic field

Variable	Type	Units	Default	Meaning
IBIFUN	I	(-)	0	Flag used to specify the behaviour of the magnetic field in time and space (-1) user's defined, through external function EXTB to be linked with the code (0) constant in time and linear in space between the values BISS and BOSS at inlet and outlet respectively (1) Current related decay in time of a linear distribution in space. The linear distribution at any time is the sum of the steady state distribution determined as for IBIFUN=0 (between BISS and BOSS) and of a transient distribution proportional to the operating current between the values BITR and BOTR at inlet and outlet respectively
BISS	R	(T)	0.0	Value of the steady state component of the magnetic field at the coil inlet
BOSS	R	(T)	0.0	Value of the steady state component of the magnetic field at the coil outlet
BITR	R	(T)	0.0	Value of the transient component of the magnetic field at the coil inlet
BOTR	R	(T)	0.0	Value of the transient component of the magnetic field at the coil outlet

Initial and boundary conditions

Variable	Type	Units	Default	Meaning
INTIAL	I	(-)	0	Flag used to specify the initial and boundary conditions for the transient. An approximate initial condition is computed in the case of initial flow. In the case of variable boundary conditions the external function EXTR is called to set the boundary pressure and temperature as a function of time. The type of boundary condition selected is indicated in the output file as input echo. (0) user's defined, through external function EXTA to be linked with the code (1) inlet and outlet pressure and inlet temperature are given. The initial flow and variable distribution are computed from the pressure drop. The boundaries for the flow are at constant pressure and temperature (as established from the initial distribution) (-1) as for (1) but boundary pressure and temperature can be variable in time at inlet and outlet through the user routine EXTR (2) inlet pressure, temperature and massflow are given. The initial flow and variable distribution are computed from the inlet pressure and mass flow. The boundaries for the flow are at constant pressure and temperature (as established from the initial distribution) (-2) as for (2) but boundary pressure and temperature can be variable in time at inlet and outlet through the user routine EXTR (3) inlet pressure, and temperature are given, the outlet is closed. The initial distribution is of zero flow and con stant p,T. The boundary conditions are constant pressure and temperature at the inlet and closed outlet. This choice simulates a symmetry at the outlet (-3) as for (3) but boundary pressure and temperature can be variable in time at inlet through the user routine EXTR (4) initial pressure and temperature given, closed system assumed. The initial dis tribution is of zero flow and constant p,T along the flow path. The boundary conditions are of closed inlet and outlet

PREINL	R	(Pa)	0.0	He pressure at the flow path inlet, used in the case INTIAL=1, INTIAL=2 and INTIAL=3
PREOUT	R	(Pa)	0.0	He pressure at the flow path outlet, used in the case INTIAL=1 only. Computed in the case INTIAL=2 (specified massflow).
TEMINL	R	(K)	0.0	He temperature at the flow path inlet, used in the cases INTIAL=1, INTIAL=2 and INTIAL=3. Note that in the two cases INTIAL=1 and INTIAL=2 the inlet reservoir has a temperature equal to TEMINL only for positive massflow (inlet to outlet). In the case of negative massflow (outlet to inlet) the inlet reservoir has temperature equal to TEMOUT.
TEMOUT	R	(K)	0.0	He temperature at the flow path outlet, used in the cases INTIAL=1 and INTIAL=2. Note that the outlet reservoir has a temperature equal to TEMOUT only for negative massflow (outlet to inlet). In the case of positive massflow (inlet to outlet) the outlet reservoir has temperature equal to TEMINL.
MDTINL	R	(Kg/s)	0.0	He massflow at the flow path inlet, used in the case INTIAL=2. Computed in the case INTIAL=1 (specified pressure drop)
PREINI	R	(Pa)	0.0	He initial pressure in the flow path used in the case INTIAL=4
TEMINI	R	(K)	0.0	He initial temperature in the flow path used in the case INTIAL=4

External heating

Variable	Type	Units	Default	Meaning
IQFUN	I	(-)	0	Flag used to specify the heating input (-1) user's defined, through external function EXTQ to be linked with the code (0) square wave in space and time. The power Q0 per unit length is input for a time TAUQ in the region XQBEG < x < XQEND
Q0	R	(W/m)	0.0	Linear heat flux input in the conductor when IQFUN=0
TAUQ	R	(s)	0.0	Heating time when IQFUN=0. The power is applied for 0 < t < TAUQ. Note that TAUQ is used in any case for the decision on recovery or quench in a transient. Therefore if a meaningful decision is requiored, the user must set it even in the case that the ehating is defined through the external routine EXTQ. Its meaning in this case is the time after which all heating fluxes are zero.
XQBEG	R	(m)	0.0	For IQFUN=0 beginning of the heated region
XQEND	R	(m)	0.0	For IQFUN=0 end of the heated region

Mesh and time stepping definitions. Operation flags

Variable	Type	Units	Default	Meaning
NELEMS	I	(-)	0	Total number of elements in the mesh
XLENGT	R	(m)	0.0	Total length of the cooling channel
ITYMSH	I	(-)	0	Flag used to specify the mesh type. Static (i.e. non-adaptive) and dynamic (i.e. adaptive) meshes can be requested) (-1) user's defined, the mesh is set in the external function EXTM (to be linked with the code) at each time step. The user is requested to adapt the mesh (if desired and necessary) (0) stayic uniform spacing in the length XLENGT with NELEMS elements. (1) static locally refined in the region XBREFI < x < XEREFI. A total of NELEMS elements are generated in the cooling path of length XLENGT, of which NELREF are in the refined region. (2) dynamic (adaptive) with initial uniform spacing in the length XLENGT with NELEMS elements. The mesh is adaptive with minimum and maximum mesh sizes determined by the SIZMIN and SIZMAX parameters (3) dynamic (adaptive) with initial local refinement in the region XBREFI < x < XEREFI. A total of NELEMS elements are generated in the cooling path of length XLENGT, of which NELREF are in the refined region. The mesh is adaptive with minimum and maximum mesh sizes determined by the SIZMIN and SIZMAX parameters
XBREFI	R	(m)	0.0	Beginning of the initial (t=0) refinement region
XEREFI	R	(m)	0.0	End of the initial (t=0) refinement region
NELREF	I	(-)	0	Number of elements in the refined region. It is limited by the total number of element in the flow path as follows: NELREF < NELEMS-2

SIZMIN	R	(m)	0.0	minimum allowed element size (this is the element size used in the vicinity of the normal fronts)
SIZMAX	R	(m)	0.0	maximum allowed element size. Note hat any initial element longer than SIZMAX will be automatically refined during the time stepping
METHOD	I	(-)	0	Flag used for the selection of the time integration method and space upwind (0) a globally first order accurate (in space and time) method is used (smooth but less accurate answers) (1) a globally second order accurate (in space and time) method is used (sharper front resolution, but it is possible that wiggles are created at the fronts)
TEND	R	(s)	0.0	Final time for the time integration
STPMIN	R	(s)	0.0	minimum allowed time step
STPMAX	R	(s)	0.0	maximum allowed time step
PSTEP	R	(s)	0.0	print-out time step. The output to gandalf.output output every PSTEP seconds of real time
GSTEP	R	(s)	0.0	storage time step. The output to gandalf.store (storage for post-processing and restart) is output every GSTEP seconds of real time
IRESTA	I	(-)	0	Flag used to indicate the run type (0) first run. All variables are set (1) restart run. The last time step stored is recovered from gandalf.store
ISTORP	I	(-)	0	Flag to require the storage of the results each GSTEP seconds of real time (0) no storage performed. WARNING: in this case neither post-processing, nor restarting is possible (1) storage performed
MONITR	I	(-)	0	Flag activating the interactive monitor for on-line visualization of the dynamics (experimental feature) (0) no interactive monitor (1) ineractive monitor

External Routines

The following sections describe routines that are provided as an interface for the user to improve the modelling capabilities of GANDALF. These routines are either provided as dummy (void) procedures, in the case that they are not needed for the standard execution of the code, or contain general purpose relations (such as the case for EXTF for the friction factor and the routines of the EXTHxx series for the heat transfer coefficients) in the case that they are used in the standard code execution.

Note: FORTRAN unit numbers above 50 are reserved for internal use

Cross sections

```
SUBROUTINE EXTCAB       (NOD    ,X     ,ASC   ,AST   ,AJK   ,AIN   ,
                         PHTC   ,PHTJ  ,PHTCJ ,ASC_X ,AST_X ,AJK_X ,
                         AIN_X  ,PHTC_X,PHTJ_X,PHTCJ_X)
```

Returns the cable cross sections and wetted perimeter as a function of the position along the cable

List of variables:

Variable	Type	I/O	Units	Meaning
NOD	I	I	(-)	Node number
X	R	I	(m)	Nodal coordinate
ASC	R	I	(m^2)	Superconductor cross section (as from input)
AST	R	I	(m^2)	Stabilizer cross section (as from input)
AJK	R	I	(m^2)	Jacket cross section (as from input)
AIN	R	I	(m^2)	Insulation cross section (as from input)
PHTC	R	I	(m)	Heat transfer perimeter at the contact surface of the conductor and *bundle* helium channel (as from input)
PHTJ	R	I	(m)	Heat transfer perimeter at the contact surface of the jacket and *bundle* helium channel (as from input)
PHTCJ	R	I	(m)	Heat transfer perimeter at the contact surface of the conductor and jacket (used to model the contact resistance) (as from input)
ASC_X	R	O	(m^2)	Superconductor cross section at node NOD
AST_X	R	O	(m^2)	Stabilizer cross section at node NOD
AJK_X	R	O	(m^2)	Jacket cross section at node NOD
AIN_X	R	O	(m^2)	Insulation cross section at node NOD
PHTC_X	R	O	(m)	Heat transfer perimeter at the contact surface of the conductor and *bundle* helium channel at node NOD
PHTJ_X	R	O	(m)	Heat transfer perimeter at the contact surface of the jacket and *bundle* helium channel at node NOD
PHTCJ_X	R	O	(m)	Heat transfer perimeter at the contact surface of the conductor and jacket (used to model the contact resistance) at node NOD

```
SUBROUTINE EXTCHN       (NOD   ,X     ,AHEH  ,AHEB  ,DHH   ,DHB   ,
                         PHTHB ,PERFOR,AHEH_X,AHEB_X,DHH_X ,DHB_X ,
                         PHTHB_X,PERFOR_X)
```

Returns the channel cross sections, hydraulic diameter, wetted perimeter between channels and perforation as a function of the position along the cable

List of variables:

Variable	Type	I/O	Units	Meaning
NOD	I	I	(-)	Node number
X	R	I	(m)	Nodal coordinate
AHEH	R	I	(m^2)	Cross section of the *hole* helium channel (as from input)
AHEB	R	I	(m^2)	Cross section of the *bundle* helium channel (as from input)
DHH	R	I	(m)	Hydraulic diameter of the *hole* helium channel (as from input)
DHB	R	I	(m)	Hydraulic diameter of the *bundle* helium channel (as from input)
PHTHB	R	I	(m)	Heat transfer perimeter at the contact surface of the *hole* and *bundle* helium channels (as from input)
PERFOR	R	I	(m)	Percentage perforation of the wetted perimeter between *hole* and *bundle* helium channels (as from input)
AHEH_X	R	O	(m^2)	Cross section of the *hole* helium channel at node NOD
AHEB_X	R	O	(m^2)	Cross section of the *bundle* helium channel at node NOD
DHH_X	R	O	(m)	Hydraulic diameter of the *hole* helium channel at node NOD
DHB_X	R	O	(m)	Hydraulic diameter of the *bundle* helium channel at node NOD
PHTHB_X	R	O	(m)	Heat transfer perimeter at the contact surface of the *hole* and *bundle* helium channels at node NOD
PERFOR_X	R	O	(m)	Percentage perforation of the wetted perimeter between *hole* and *bundle* helium channels at node NOD

Coil current

```
SUBROUTINE EXTI          (TIME   ,TSTEP ,IOP0   ,RSSTNC,IOP    )
```

Compute the operating current as an arbitrary function of time and coil resistance.

List of variables:

Variable	Type	I/O	Units	Meaning
TIME	R	I	(s)	Real time in the integration
TSTEP	R	I	(s)	Time step to be taken
IOP0	R	I	(A)	Initial current (t=0)
RSSTNC	R	I	(Ohm)	Coil resistance
IOP	R	O	(A)	Coil current

Magnetic field

```
SUBROUTINE EXTB          (TIME   ,X      ,NOD    ,IOP    ,B      )
```

Compute the magnetic field as an arbitrary function of time,space and current

List of variables:

Variable	Type	I/O	Units	Meaning
TIME	R	I	(s)	Real time in the integration
X	R	I	(m)	Nodal coordinate
NOD	I	I	(-)	Node number
IOP	R	I	(A)	Coil current
B	R	O	(T)	Magnetic field

External heat input

```
SUBROUTINE EXTQ          (TIME  ,TSTEP ,X      ,NOD   ,
                          QO    ,XQBEG ,XQEND  ,TAUQ  ,
                          TCO   ,TJK   , QFLUXC,QFLUXJ)
```

Compute the heat perturbation as an arbitrary function of time and space. The routine returns the value of the heating flux QFLUXC and QFLUXJ at the time TIME and position X (also identified by the node index NOD). Note that the parameters read-in from the input namelist (see input parameters list) are passed to the routine (as *trimming* set) although they are in effect not used in the main program (but can be used in principle in EXTQ).

List of variables:

Variable	Type	I/O	Units	Meaning
TIME	R	I	(s)	Real time in the integration
TSTEP	R	I	(s)	Time step to be taken
X	R	I	(m)	Nodal coordinate
NOD	I	I	(-)	Node number
Q0	R	I	(W/m)	Linear heat flux (as from input)
XQBEG	R	I	(m)	Start of the heated region (as from input)
XQEND	R	I	(m)	End of the heated region (as from input)
TAUQ	R	I	(s)	Heating time (as from input)
TCO	R	I	(K)	Conductor temperature
TJK	R	I	(K)	Jacket temperature
QFLUXC	R	O	(W/m)	Heating linear flux in the conductor
QFLUXJ	R	O	(W/m)	Heating linear flux in the jacket

External boundary conditions

```
SUBROUTINE EXTR          (TIME  ,TSTEP ,PREINL,TEMINL,MDTINL,
                          PREOUT,TEMOUT,PREINI,TEMINI,P     ,
                          T     ,R     ,MDOT  ,PIN   ,TIN   ,
                          POUT  ,TOUT  )
```

Set the boundary conditions for the flow calculation (pressure and temperature at inlet and outlet of the flow-path) as a function of time and of the flow conditions in the flow path. The routine returns the value of the inlet pressure and temperature PIN and TIN and the outlet values POUT and TOUT which are used as boundary conditions for the transient. Note that the parameters read-in from the input namelist (see input parameters list) are passed to the routine (as *trimming* set) although they are in effect not used in the main program (but can be used in principle in EXTR). Also passed are the computed parameters of outlet temperature or initial massflow.

List of variables:

Variable	Type	I/O	Units	Meaning
TIME	R	I	(s)	Real time in the integration
TSTEP	R	I	(s)	Time step to be taken
PREINL	R	I	(Pa)	Initial inlet pressure (as from input)
TEMINL	R	I	(K)	Initial inlet temperature (as from input)
MDTINL	R	I	(Kg/s)	Initial inlet flow (as from input or computed)
PREOUT	R	I	(Pa)	Initial outlet pressure (as from input or computed)
TEMOUT	R	I	(K)	Initial outlet temperature (as computed)
PREINI	R	I	(Pa)	Initial pressure in case of zero flow (as from input)
TEMINI	R	I	(K)	Initial temperature in case of zero flow (as from input)
P	R	I	(Pa)	array (of dimension 2) containing the pressure at the previous step in the first (inlet) and last (outlet) node of the flowpath
T	R	I	(K)	array (of dimension 2) containing the temperature at the previous step in the first (inlet) and last (outlet) node of the flowpath
R	R	I	(Kg/m^3)	array (of dimension 2) containing the density at the previous step in the first (inlet) and last (outlet) node of the flowpath
MDOT	R	I	(Kg/s)	array (of dimension 2) containing the massflow at the previous step in the first (inlet) and last (outlet) node of the flowpath
PIN	R	O	(Pa)	Inlet pressure
TIN	R	O	(K)	Inlet temperature
POUT	R	O	(Pa)	Outlet pressure
TOUT	R	O	(K)	Outlet temperature

User's defined mesh

```
SUBROUTINE EXTM          (NELEMS,NNODES,XLENGT,ITYMSH,XBREFI,
                          XEREFI,NELREF,XCOORD)
```

Set the mesh in the array XCOORD, called when the flag ITYMSH is set to -1. Note that this mesh design routine is called at each time step to allow the user to perform adaptivity.

List of variables:

Variable	Type	I/O	Units	Meaning
NELEMS	I	I/O	(-)	Number of elements at the last time step (at the initial call the value from input is given). The new number of elements must be returned from the call
NNODES	I	I/O	(-)	Number of nodes at the last time step (at the initial call the value from input is given). The new number of nodes must be returned from the call
XLENGT	R	I	(m)	Length of the cable (as from input)
ITYMSH	I	I	(-)	Mesh type (as from input)
XBREFI	R	I	(m)	Beginning of refinement (as from input)
XEREFI	R	I	(m)	End of refinement (as from input)
NELREF	I	I	(-)	Number of elements within the refined region (as from input)
XCOORD	R	O	(K)	Array of dimension NNODES containing the coordinates of each node

Electrical and thermal properties of user's defined materials

These functions substitue the default material properties in case of negative material flags ISC, IST, IJK or IIN. They can be designed to provide an extension to the CryoSoft library `Solids`. For this purpose the material `Material` can be used as a univoque index referring to a specific material. The routines below can provide the appropriate switch between materials, and perform the necessary property calculation.

Density

```
FUNCTION UserDensity     (Material ,T)
```

Used to compute the density of a user's defined material

List of variables:

Variable	Type	I/O	Units	Meaning
`Material`	I	I	(-)	Material flag, as from input
`T`	R	I	(K)	temperature
`UserDensity`	R	O	(Kg/m^3)	density

Specific heat

```
FUNCTION UserSpecificHeat      (Material ,T    ,B    ,Tcs    ,EPSLON)
```

Used to compute the specific heat of a user's defined material

List of variables:

Variable	Type	I/O	Units	Meaning
`Material`	I	I	(-)	Material flag, as from input
`T`	R	I	(K)	temperature
`B`	R	I	(T)	Magnetic field
`Tcs`	R	I	(K)	current sharing temperature
`EPSLON`	R	I	(-)	longitudinal strain
`UserSpecificHeat`	R	O	(J/Kg K)	specific heat

Thermal conductivity

```
FUNCTION UserConductivity      (Material ,T  ,B ,RRR)
```

Used to compute the thermal conductivity of a user's defined material

List of variables:

Variable	Type	I/O	Units	Meaning
Material	I	I	(-)	Material flag, as from input
T	R	I	(K)	temperature
B	R	I	(T)	Magnetic field
RRR	R	I	(-)	residual resistivity ratio
UserConductivity	R	O	(W/m K)	thermal conductivity

Electrical resistivity

```
FUNCTION UserResistivity       (Material ,T   ,B   ,RRR)
```

Used to compute the electrical resistivity of a user's defined material

List of variables:

Variable	Type	I/O	Units	Meaning
Material	I	I	(-)	Material flag, as from input
T	R	I	(K)	temperature
B	R	I	(T)	Magnetic field
RRR	R	I	(-)	residual resistivity ratio
UserResistivity	R	O	(Ohm m)	electrical resistivity

Critical current density

```
FUNCTION UserCriticalCurrent  (Material ,T  ,B ,EPSLON)
```

Used to compute the critical current density of a user's defined superconducting material

List of variables:

Variable	Type	I/O	Units	Meaning
Material	I	I	(-)	Material flag, as from input
T	R	I	(K)	temperature
B	R	I	(T)	Magnetic field
EPSLON	R	I	(-)	longitudinal strain
UserCriticalCurrent	R	O	(A/m^2)	critical current density

Critical temperature

```
FUNCTION UserCriticalTemperature    (Material ,B ,EPSLON)
```

Used to compute the critical temperature of a user's defined superconducting material

List of variables:

Variable	Type	I/O	Units	Meaning
Material	I	I	(-)	Material flag, as from input
B	R	I	(T)	Magnetic field
EPSLON	R	I	(-)	longitudinal strain
UserCriticalTemperature	R	O	(K)	critical temperature

Current sharing temperature

```
FUNCTION UserCurrentSharing   (Material ,B ,JOP   ,EPSLON)
```

Used to compute the current sharing temperature of a user's defined superconducting material

List of variables:

Variable	Type	I/O	Units	Meaning
Material	I	I	(-)	Material flag, as from input
B	R	I	(T)	Magnetic field
JOP	R	I	(A/m^2)	operating current density
EPSLON	R	I	(-)	longitudinal strain
UserCurrentSharing	R	O	(K)	current sharing temperature

Friction factor

```
SUBROUTINE EXTF          (CHNNEL ,X    ,NOD    ,REYNOL ,FRICTN)
```

Compute the friction factor of the flow for helium in the cooling hole or in the cable bundle. Must ALWAYS be present for the calculation of the flow

List of variables:

Variable	Type	I/O	Units	Meaning
CHNNEL	I	I	(-)	1=bundle 2=hole
X	R	I	(m)	Nodal coordinate
NOD	I	I	(-)	Node number
REYNOL	R	I	(-)	Reynolds number
FRICTN	R	O	(-)	Friction factor

Heat transfer coefficient

These functions define the heat transfer coefficient of the flow in the channels, and the equivalent transfer coefficients corresponding to thermal resistances. These functions ALWAYS be present for the calculation of the energy exchange among components.

Conductor-bundle heat transfer coefficient

```
SUBROUTINE EXTHCB        (TIME   ,X      ,NOD     ,T      ,P      ,D      ,
                          TWALL  ,DH     ,REYNOL  ,HTC_CB)
```

Compute the conductor-bundle helium heat transfer coefficient (in $W/m^2 K$)

List of variables:

Variable	Type	I/O	Units	Meaning
TIME	R	I	(s)	Real time in the integration
X	R	I	(m)	Nodal coordinate
NOD	I	I	(-)	Node number
T	R	I	(K)	Helium temperature
P	R	I	(Pa)	Helium pressure
D	R	I	(Kg/m^3)	Helium density
TWALL	R	I	(K)	Wall (conductor) temperature
DH	R	I	(m)	Hydraulic diameter
REYNOL	R	I	(-)	Reynolds number
HTC_CB	R	O	(W/m^2K)	Conductor-bundle heat transfer coefficient

Conductor-jacket equivalent heat transfer coefficient

```
SUBROUTINE EXTHCJ        (TIME   ,X      ,NOD     ,TCO   ,TJK   , HTC_CJ)
```

Compute the heat transfer coefficient (in $W/m^2 K$) equivalent to the thermal resistance between the strands in the conductor and the jacket.

List of variables:

Variable	Type	I/O	Units	Meaning
TIME	R	I	(s)	Real time in the integration
X	R	I	(m)	Nodal coordinate
NOD	I	I	(-)	Node number
TCO	R	I	(K)	Helium temperature in the conductor
TJK	R	I	(K)	Helium temperature in the jacket
HTC_CJ	R	O	($W/m^2 K$)	Conductor-jacket heat transfer coefficient

Jacket-bundle wall equivalent heat transfer coefficient

```
SUBROUTINE EXTHJB       (TIME  ,X     ,NOD    ,T     ,P     ,D     ,
                         TWALL ,DH    ,REYNOL ,HTC_JB)
```

Compute the heat transfer coefficient (in W/m^2 K) equivalent to the jacket-bundle wall thermal resistance.

List of variables:

Variable	Type	I/O	Units	Meaning
TIME	R	I	(s)	Real time in the integration
X	R	I	(m)	Nodal coordinate
NOD	I	I	(-)	Node number
T	R	I	(K)	Helium temperature
P	R	I	(Pa)	Helium pressure
D	R	I	(Kg/m^3)	Helium density
TWALL	R	I	(K)	Wall (jacket) temperature
DH	R	I	(m)	Hydraulic diameter
REYNOL	R	I	(-)	Reynolds number
HTC_JB	R	O	(W/m^2K)	Jacket-bundle heat transfer coefficient

Hole-bundle mixing heat transfer coefficient

```
SUBROUTINE EXTHHB       (TIME  ,X     ,NOD   ,THEH  ,THEB  ,PH    ,
                         PB    ,VH    ,VB    ,DENH  ,DENB  ,DHH   ,
                         DHB   ,REYNOH,REYNOB,FRICTH,FRICTB,PERFOR,
                         HTC_HB)
```

Compute the mixing heat transfer coefficient (in W/m^2 K) between hole and bundle channels.

List of variables:

Variable	Type	I/O	Units	Meaning
TIME	R	I	(s)	Real time in the integration
X	R	I	(m)	Nodal coordinate
NOD	I	I	(-)	Node number
THEH	R	I	(K)	Helium temperature in the hole
THEB	R	I	(K)	Helium temperature in the bundle
PH	R	I	(Pa)	Helium pressure in the hole
PB	R	I	(Pa)	Helium pressure in the bundle
VH	R	I	( )	Helium velocity in the hole
VB	R	I	( )	Helium velocity in the bundle
DENH	R	I	( )	Helium density in the hole
DENB	R	I	( )	Helium density in the bundle
DHH	R	I	(m)	Hydraulic diameter of the hole

DHB	R	I	(m)	Hydraulic diameter of the bundle
REYNOH	R	I	(-)	Reynolds number in the hole
REYNOB	R	I	(-)	Reynolds number in the bundle
FRICTH	R	I	(-)	Friction factor in the hole
FRICTB	R	I	(-)	Friction factor in the bundle
PERFOR	R	I	(-)	bundle-hole perforation (as from input)
HTC_HB	R	O	[W/m^2 K]	Hole-bundle heat transfer coefficient

Quality indicators and general guidelines for running

As mentioned in the introduction, a number of quality indicators is computed by *GANDALF* to judge the solution obtained. In general, a quench simulation can produce *wrong* results because of large diffusivity in the scheme chosen, and because the numerical approximations cause over-propagation of the quench front, thus triggering a non-linear process that makes the numerical solution diverge from the physical one. Therefore a check must be made on:

a) the amount of numerical diffusion of the scheme used, and
b) the amount of numerical propagation of the fronts.

Two solution schemes are available in *GANDALF*. They are either a first-order accurate Euler-Backward implicit integrator with upwinding (METHOD=0), or a second-order accurate Crank-Nicolson implicit integrator without upwinding (METHOD=1). The first has numerical diffusivity built in, used to stabilize the scheme, while the second has not. To clarify better the performance of the two schemes, while the first smear fronts and makes every solution smooth (sometimes unphysically), the second tries to represent as faithfully as possible discontinuities in the solution, thus suffering from oscillation paranoia at sharp fronts. Therefore if strong discontinuities are present in the solution (large temperature gradients moving along the cable) a good choice is to use the first order scheme in these situations. The draw-back is the lower accuracy, that requires a much finer mesh and smaller steps. Thus for efficiancy and accuracy, the user should try to use the second order scheme as soon (or as often) as possible.

The error and quality indicators computed try to quantify the considerations above. They are:

a) the maximum numerical diffusion of the scheme, and
b) the estimated numerical propagation at the fronts.

While the first can be computed exactly for both schemes (and is evidently zero for the second order scheme), for the second only an analytical approximation can be given. The two indicators above must be compared to the physical diffusivity and to the physical propagation speed diffusivity, checking that the ratio of numerical to physical quantity is smaller than 1. Again, while the first can be given exactly, based on the material properties, the second is not known (were it known, we would be in no trouble…). A good compromise is to compare the numerical estimated propagation speed to the total computed propagation speed. Note that we must require the ratio to be in this case MUCH smaller than 1 (for a small numerical perturbation can result in long term physical drifts). *GANDALF* computes the sum of the numerical front propagations (taken in absolute terms) and the ratio of this sum to the total propagation speed (the time derivative of the total normal length). Note that this is different from the front speed (typically by a factor given by the number of travelling fronts). This choice has been made because it is independent on the actual front position, on the number of fronts, and on their single speed.

Typically, an acceptable value for the ratio of numerical to total proagation speed is in the range of some 1 to 5 %. This ratio is the most valuable quality indicator provided. In fact, in case of adaptive meshing, some regions of the mesh can have large elements, and thus the ratio of numerical to physical diffusivity can be locally very large, but irrelevant to quench propagation. This last can be used to check the quality of the solution when a fixed mesh is used, as, e.g., in the analysis of cooling of a coil in pulsed mode. The acceptance limit in this case can be larger, typically up to 10 %.

The tolerance values given above result, for a generic cable with void fraction of the order of 50 %, Copper:Non-copper ratio in the range of 2 and operating cable space current density of the order of 50 A/mm^2 in typical mesh sizes below 1 mm and step below 1 ms for the first order scheme, below 1 cm and below 5 ms for the second order scheme. The cryticality of the first order scheme is evident, as CPU time and memory can become a factor 5 to 10 higher.

For future development, a last, additional error indicator is computed by *GANDALF*. It is based on an estimate of the interpolation error of a control variable U, in this case the conductor temperature. The second derivative of the control variable is computed at the nodes, and the rms interpolation error is estimated locally as:

$$\varepsilon = \frac{1}{11}\Delta x^2 \left| \frac{d^2U}{dx^2} \right|$$

where Δx is the element size (averaged at the nodes). This gives a nodal indication of the error. The maximum error and the ratio of this maximum to the maximum of the control variable (i.e. the $\bullet$-*norm*) are used as indications of the amount of error. Note that this error indicator cannot be used to identify numerical front propagation and numerical diffusivity, as the higher the numerical propagation and the diffusivity of the scheme, the smoother the solution becomes. The are intended for future use in the control of the mesh for transient problems wich do not involve quench propagation, or for areas of the cable far from the propagating fronts.

The error and quality indicators are output on the main listing (header of nodal results) and stored on the post-processing file. They can be accessed for plotting or table creation through the post-processing commands (see later). As said in the introduction, the control of the quality of the solution is left to the user, whose responsibility is to make sure that the indicators are below tolerable levels.

Error Codes

A limited number of checks are performed in the input phase to insure that the data set is consistent and that the memory requirements for the solution of the problem do not exceed the availability. An error message is printed on the main output unit in case that one of these checks is not passed. The error message gives a numeric code which corresponds to the following table. Lists in braces indicate allowed values.

Code	Error	Meaning and corrective action
1	NNODES>MAXNOD	Number of nodes exceeds the maximum allowed. Increase the MAXNOD parameter in the main code
2	NELEMS □ 0	Wrong definition of the number of elements is given in input. Correct input.
10	ISC > 0 and ISC ≠{31,32)	The flag for the superconductor type has a wrong value. Correct ISC in input
11	IST ≥ 0 and IST ≠ {1,2}	The flag for the stabilizer type has a wrong value. Correct IST in input
12	IJK ≥ 0 and IJK ≠ {1,2,3,11,13,14,15}	The flag for the jacket type has a wrong value. Correct IJK in input
13	IIN ≥ 0 and IIN ≠ {21,22,23)	The flag for the insulation type has a wrong value. Correct IIN in input
14	IOPFUN ≠ {-1,0,1}	The flag for the current behaviour has a wrong value. Correct IOPFUN in input
15	IBIFUN ≠ {-1,0,1}	The flag for the field behaviour has a wrong value. Correct IBIFUN in input
16	ITYMSH ≠ {-1,0,1,2,3}	The flag for the mesh type has a wrong value. Correct ITYMSH in input
17	INTIAL ≠ {1,2,3,4}	The flag for the initial condition has a wrong value. Correct INTIAL in input
18	IQFUN ≠ {-1,0,1}	The flag for the heating input has a wrong value. Correct IQFUN in input
19	METHOD ≠ {0,1}	The flag for the integration method has a wrong value. Correct METHOD in input

Code	Error	Meaning and corrective action
21	ISTORP ≠ {0,1}	The flag for the request of results storage has a wrong value. Correct ISTORP in input
23	IRESTA ≠ {0,1}	The flag for restart has a wrong value. Correct IRESTA in input
24	NELREF>NELEMS-2	The number of elements in the refined region (in case that ITYMSH=1 or ITYMSH=3) does not allow for enough elements in the remaining of the flow path
31	XLENGT □ 0	The length of the flow path is wrongly or not given. Correct XLENGT in input
32	ASC<0 or AST<0 or AJK<0 or AIN<0	A negative value for an area has been given in input. Correct the input value
33	ASC>0 and AST □ 0	The conductor is not stabilized. Specify a non-negative stabilizer area AST in input
34	AHEH+AHEB □ 0	No helium present in the cable. Specify a non-negative helium area AHEB (and AHEH if required) in input
35	DHH □ 0 or DHB □ 0	Negative or zero hydraulic diameter. Specify a non-negative hydraulic diameter DHH and DHB in input
36	PHTC < 0 or PHTJ < 0 or PHTCJ < 0 or PHTHB < 0	Negative wetted perimeter. Specify a non-negative wetted perimeter PHTC or PHTJ or PHTCJ or PHTHB in input
37	NPOWER □ 0	Negative or zero exponent for electric field power law. Specify a positive exponent NPOWER in input
38	E0 □ 0	Negative or zero electric field limit for the electric field power law. Specify a positive E0 in input
40	|INTIAL| = 1 and PREINL □ 0	Negative or zero pressure at inlet. Specify a non-negative helium pressure PREINL in input
41	|INTIAL| = 1 and PREOUT □ 0	Negative or zero pressure at outlet. Specify a non-negative helium pressure PREOUT in input
42	|INTIAL| = 1 and TEMINL □ 0 and PREINL ≥ PREOUT	Negative or zero temperature at inlet for an initial flow from inlet to outlet. Specify a non-negative helium temperature TEMINL in input

Code	Error	Meaning and corrective action
43	|INTIAL| = 1 and TEMOUT □ 0 and PREINL < PREOUT	Negative or zero temperature at outlet for an initial flow from outlet to inlet. Specify a non-negative helium temperature TEMOUT in input
44	|INTIAL| = 2 and TEMINL □ 0 and MDTINL >=0	Negative or zero temperature at inlet. Specify a non-negative helium temperature TEMINL in input
45	|INTIAL| = 2 and PREINL □ 0 and MDTINL >=0	Negative or zero pressure at inlet. Specify a non-negative helium pressure PREINL in input
46	|INTIAL| = 2 and TEMOUT □ 0 and MDTINL <0	Negative or zero temperature at outlet. Specify a non-negative helium temperature TEMOUT in input
47	|INTIAL| = 2 and PREOUT □ 0 and MDTINL <0	Negative or zero pressure at outlet. Specify a non-negative helium pressure PREOUT in input
48	|INTIAL| = 3 and PREINL □ 0	Negative or zero pressure at inlet. Specify a non-negative helium pressure PREINL in input
49	|INTIAL| = 3 and TEMINL □ 0	Negative or zero temperature at inlet. Specify a non-negative helium temperature TEMINL in input
50	INTIAL = 4 and PREINI □ 0	Negative or zero initial pressure. Specify a non-negative helium pressure PREINI in input
51	INTIAL = 4 and TEMINI □ 0	Negative or zero initial temperature. Specify a non-negative helium temperature TEMINI in input
52	PREINL □ 0 or PREOUT □ 0	Negative or zero pressure owing to a large specified mass flow

Code	Error	Meaning and corrective action
61	End-of-file or Read-in error	The storage file has not been found or cannot be read during a restart run
62	Input file does not exist or Read-in error	The input file has not been found or cannot be read
63	Write error or storage file	The storage file cannot be written
71	Matrix scaling error	The system matrix is singular and cannot be scaled
72	Matrix factorization error	The system matrix is singular and cannot be factorized during the inversion process
73	Matrix back-substitution error	The system matrix is singular and cannot be back-substituted during the inversion process

Post Processing

The post processing of the results of GANDALF is possible using the results stored on the storage. The actual format of the storage unit can be deduced from the routines STOROP and STORER of GANDALF (see the main code).

A dedicated program has been written for generation of plots and writing of report files (in order to have the possibility to store and successively generate plots). The program, GANDALF_POST, is based on a PostScript™ graphic library and can generated Adobe-PostScript™ ASCII files for plotting.

The input for the program is the storage file generated by the solver GANDALF on gandalf.store, and a terminal sequence or a command file.

Outputs are generated as plots and an ASCII report (with tables of distributions and evolutions) can be written to g1dp.tables. In addition, two scratch files are used for read, storage and write operations.

Command language for the post processors

Here follows the list of the commands of GANDALF_POST. Note that for all keywords only the first 4 characters are necessary (indicated in upper case). A ';' character in any position of a command line indicates a comment or end-of-line (the remaining of the line is ignored). Commands can be entered both in upper- and lowercase.

Command	Options	Meaning
STOP		Stop execution and close the session
LIST		List the times stored on the storage unit
POST	ON/OFF	Switch ON or OFF (default) the writing of the post processing ASCII tables on file `g1dp.tables`
PLOT	ON/OFF	Switch ON (default) or OFF the PostScript™ output (plots)
TABLe		Start table definition. The post-processing commands following the TABLe command generate a packed table of data if POST is ON. The table is completed (and output) as soon as the ENDTable command is found. Ignored if POST is OFF
ENDTable		End table definition

Command	Options		Meaning
ECHO	ON		
	OFF		Turn the echo of commands ON or OFF
HISTory			Plot/output the history as f(t) of:
	T_COnductor		conductor temperature
	T_JAcket		jacket temperature
	T_HElium		helium temperature
	T_HBundle		helium temperature in the bundle
	T_HHole		helium temperature in the hole
	PRESssure		helium pressure
	PR_Bundle		helium pressure in the bundle
	PR_Hole		helium pressure in the hole
	DENSity		helium density
	DENBundle		helium density in the bundle
	DENHole		helium density in the hole
	V_Hole		helium velocity in the hole
	V_BUndle		helium velocity in the bundle
	VELOcity		averaged helium velocity
	M_HOle		helium mass flow in the hole
	M_BUndle		helium mass flow in the bundle
	MASS_flow		total helium mass flow
	RE_Hole		helium reynolds number in the hole
	RE_Bundle		helium reynolds number in the bundle
	H_CHole		heat transfer coefficient conductor-hole
	H_CBundle		heat transfer coefficient conductor-bundle
	H_JHole		heat transfer coefficient jacket- hole
	H_JBundle		heat transfer coefficient jacket-bundle
	H_CJacket		heat transfer coefficient conductor-jacket
	H_HBundle		heat transfer coefficient hole-bundle
	B		magnetic field
	Q_EConductor		external linear heat flux in the strands
	Q_EJacket		external linear heat flux in the jacket
	Q_JConductor		joule heat flux in the conductor
	Q_JJacket		joule heat flux in the jacket
	Q_CConductor		cooling flux from the conductor to the helium
	Q_CJacket		cooling flux from the jacket to the helium
	J_CRitical		critical current
	T_CRitical		critical temperature
	T_CS		current sharing temperature
	T_MArgin		temperature margin
	F_OPeration		operating fraction of the critical current
		NODE *n*	at the node number *n*
		X *x*	at a length *x* from inlet (interpolation is performed between the closest nodes)

Command	Options	Meaning
HISTory		Plot/output the history of:
	CURRent	current
	RESIstance	resistance
	VOLTage	voltage
	NORMal	normal zone length
	PROPagation	computed instantaneous total propagation speed (time derivative of the TOTAL normal length)
	P_JOule	total Joule heat power in the mesh (integrated over the length)
	P_EXternal	total external power in the mesh (integrated over the length)
	E_JOule	total Joule energy deposited in the mesh (integral in time of the Joule power)
	E_EXternal	total external energy deposited in the mesh (integral in time of the external power)
	DIFFusivity	Maximum numerical diffusivity
	DIFRelative	Maximum ratio of numerical to physical diffusivity
	PNUMerical	Estimated numerical total propagation speed
	PNURelative	Ratio of numerical to computed total propagation speed
	INTErpolation	Estimated interpolation error on the conductor temperature
	INTRelative	Estimated relative interpolation error on the conductor temperature

Command	Options		Meaning
DISTribution			Plot/output the distribution as f(x) of
	T_COnductor		conductor temperature
	T_JAcket		jacket temperature
	T_HElium		averaged helium temperature
	T_HBundle		helium temperature in the bundle
	T_HHole		helium temperature in the hole
	PRESssure		averaged helium pressure
	PR_Bundle		helium pressure in the bundle
	PR_Hole		helium pressure in the hole
	DENSity		helium density
	DENBundle		helium density in the bundle
	DENHole		helium density in the hole
	V_Hole		helium velocity in the hole
	V_BUndle		helium velocity in the bundle
	VELOcity		averaged helium velocity
	M_HOle		helium mass flow in the hole
	M_BUndle		helium mass flow in the bundle
	MASS_flow		total helium mass flow
	RE_Hole		helium reynolds number in the hole
	RE_Bundle		helium reynolds number in the bundle
	H_CHole		heat transfer coefficient conductor-hole
	H_CBundle		heat transfer coefficient conductor-bundle
	H_JHole		heat transfer coefficient jacket- hole
	H_JBundle		heat transfer coefficient jacket-bundle
	H_CJacket		heat transfer coefficient conductor-jacket
	H_HBundle		heat transfer coefficient hole-bundle
	B		magnetic field
	Q_EConductor		external linear heat flux in the strands
	Q_EJacket		external linear heat flux in the jacket
	Q_JConductor		joule heat flux in the conductor
	Q_JJacket		joule heat flux in the jacket
	Q_CConductor		cooling flux from the conductor to the helium
	Q_CJacket		cooling flux from the jacket to the helium
	J_CRitical		critical current
	T_CRitical		critical temperature
	T_CS		current sharing temperature
	T_MArgin		temperature margin
	F_OPeration		operating fraction of the critical current
	MESH_density		mesh density (inverse of the element length)
	TIMEs	n	
		$t_1,t_2...t_n$	at n times in sequence given by $t_1,t_2,...t_n$ (the closest time stored is found and plotted)
			The distribution curves are marked by an identifier and a legend is plotted with the recovered times

Command	Options	Meaning
3_D		Plot a pseudo-3D f(x,t) distribution of:
	T_COnductor	conductor temperature
	T_JAcket	jacket temperature
	T_HElium	averaged helium temperature
	T_HBundle	helium temperature in the bundle
	T_HHole	helium temperature in the hole
	PRESssure	averaged helium pressure
	PR_Bundle	helium pressure in the bundle
	PR_Hole	helium pressure in the hole
	DENSity	helium density
	DENBundle	helium density in the bundle
	DENHole	helium density in the hole
	V_HOle	helium velocity in the hole
	V_BUndle	helium velocity in the bundle
	VELOcity	averaged helium velocity
	M_HOle	helium mass flow in the hole
	M_BUndle	helium mass flow in the bundle
	MASS_flow	total helium mass flow
	RE_Hole	helium reynolds number in the hole
	RE_Bundle	helium reynolds number in the bundle
	H_CHole	heat transfer coefficient conductor-hole
	H_CBundle	heat transfer coefficient conductor-bundle
	H_JHole	heat transfer coefficient jacket- hole
	H_JBundle	heat transfer coefficient jacket-bundle
	H_CJacket	heat transfer coefficient conductor-jacket
	H_HBundle	heat transfer coefficient hole-bundle
	B	magnetic field
	Q_EConductor	external linear heat flux in the strands
	Q_EJacket	external linear heat flux in the jacket
	Q_JConductor	joule heat flux in the conductor
	Q_JJacket	joule heat flux in the jacket
	Q_CConductor	cooling flux from the conductor to the helium
	Q_CJacket	cooling flux from the jacket to the helium
	J_CRitical	critical current
	T_CRitical	critical temperature
	T_CS	current sharing temperature
	T_MArgin	temperature margin
	F_OPeration	operating fraction of the critical current
	MESH_density	mesh density (inverse of the element length)
		The 3-D plot is done over the whole length and for all store times. No table output (post-processing report) is possible as the amount of data generated can be considerable

References

[1] L.Bottura, *A Numerical Model for the Simulation of Quench in the ITER Magnets*, Jour. Comp. Phys., **124**, (1), 1996.

[2] L. Bottura, *Modelling Stability in Superconducting Cables*, Physica C, **310**, 316-326, 1998.

Additional information on generalities of quench modelling and numerical techniques can be found in:

[3] L.Bottura, *Quench Analysis of Superconducting Magnets. A Numerical Study*, EC Report No. 102, EUR-FU/XII/185/93, 1993

[4] L. Bottura, C. Rosso, *Finite Element Simulation of Steady State and Transient Forced Convection in Superfluid Helium*, Int. J. Num. Meth. Fluids, **30**, 1091-1108, 1999.

Examples

Here are reported the input data for a sample run and restart performed with the basic GANDALF for a fixed, non adaptive mesh and the input file for the post-processor GANDALF_POST. Note that these inputs are intended as verifications, and do not necessarily satisfy the convergence requirements.

Input for the first run with GANDALF

```
Test Run for the manual, version 2.2
 &INDATA

      NELEMS=      200, XLENGT=    100.0, ITYMSH=        1,
      NELREF=      100, XBREFI=     40.0, XEREFI=       60,

      ICHFUN=        0,
      AHEH  =  19.6E-6, AHEB  =  71.4E-6,
      DHH   =   5.0E-3, DHB   = 0.865E-3,
      PHTHB =  15.7E-3, PERFOR=     0.01,

      ICBFUN=        0,
      ISC   =       32, ASC   =  40.6E-6,
      EPSLON=-0.250E-2, NPOWER=       30, E0    =   1.0E-4,
      IST   =        1, AST   =  60.8E-6, RRR   =    100.0,
      IJK   =       13, AJK   =  73.5E-6,
      IIN   =       22, AIN   =  61.0E-6,
      PHTC  =    0.330, PHTJ  =   5.1E-2, PHTCJ =   0.0E+0,

      INTIAL=        2,
      PREINL=  8.00E+5, TEMINL=      4.5, MDTINL=   5.0E-3,

      IOPFUN=        0, IOP0  =  8.00E+3,

      IBIFUN=        0, BISS  =     10.0, BOSS  =     10.0,

      IQFUN =        0,
      Q0    =  5.00E+4, XQBEG =     45.0, XQEND =     55.0,
      TAUQ  =  0.01000,

      TEND  = 500.0e-3, PSTEP =      0.1, GSTEP =  25.0E-3,

      STPMIN=   1.0E-7, STPMAX=   1.0E-3,

      METHOD=        0,

      ISTORP=        1, IRESTA=        0, MONITR =       1,

 &END
```

Input for the restart with GANDALF

```
Test Restart for the manual, version 2.2
 &INDATA

      TEND  =    100.0, PSTEP =      10.0, GSTEP =      1.0,

      STPMIN=   1.0E-5, STPMAX= 1000.0E-3,

      METHOD=         0,

      ISTORP=         1, IRESTA=          1, MONITR =       1,

 &END
```

Input for the post processor GANDALF_POST

```
;
; post-processing commands for test run
;

; distributions of some variables
  DIST T_CO TIME 10 .1 .2 .3 .4 .5 1 2 3 4 5
  DIST T_HH TIME 10 .1 .2 .3 .4 .5 1 2 3 4 5
  DIST T_HB TIME 10 .1 .2 .3 .4 .5 1 2 3 4 5
  DIST PR_H TIME 10 .1 .2 .3 .4 .5 1 2 3 4 5
  DIST PR_B TIME 10 .1 .2 .3 .4 .5 1 2 3 4 5
  DIST VELO TIME 10 .1 .2 .3 .4 .5 1 2 3 4 5

; hystories
  HIST T_CO X 50 HIST PRES X 50
  HIST MASS X 0  HIST MASS X 100

; pseudo 3-D plots
  3_D T_CO  3_D PRES  3_D VELO

; some quality control and errors
  HIST PROP HIST PNUM
  HIST DIFF HIST DIFR

; end of the run
  STOP
```