OPTICON

Optimisation of superconducting cables

Version 2.2

by CryoSoft

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DISCLAIMER

Introduction

OPTICON is a computer program for the optimisation of the cable fractions (stabilizer copper, superconductor, cooling helium) of a superconductor. The design criteria presently included in *OPTICON* are derived directly from Ref. [1], and guarantee:

- operation in well-cooled regime
- minimum energy or temperature margin
- maximum hot-spot temperature following a quench
- maximum hot-spot pressure following a quench

Although the present form of *OPTICON* is specifically taylored for cable-in-conduit conductors, the code can be used generally for force-cooled conductors. The user specifies the *operating point* and the *design code* through a simple set of parameters, and the program takes care, depending on the request, to choose the optimal materials and void fractions. In addition, the program gives the maximum cable space operating current density satisfying all design criteria.

The *operating point* (parameters determining the operating conditions) is specified in *OPTICON* through the following parameters (see the description of the input for details on the format)

• Operating temperature	T_{op}	(K)
• Operating field	B_{op}	(T)
• Operating field rate	dB/dt	(T/s)
(NOTE: this parameter is not yet used)		
• Operating pressure	p_{op}	(Pa)
• Discharge time constant	□	(s)
• Operating strain	□	(-)

The *design code* is the set of parameters determining the characteristics and the limits for the design. It is specified through the following parameters:

• Minimum energy margin	□E	(J/m^3)
• Minimum temperature margin	□T	(K)
• Maximum hot-spot temperature	T_{max}	(K)
• Maximum hot-spot pressure	p_{max}	(Pa)
• Strand diameter	d	(m)
• Superconductor type		(-)
• Stabilizer RRR	RRR	(-)
• Maximum strand Cu:Non-Cu ratio		(-)
• Normal length	L_n	(m)
• Average friction factor	f	(-)
• Effective heat transfer coefficient	h	(W/m^{2}K)
• Correction factor for the wetted perimeter	K_p	(-)
• Average cosine of cabling angle	cos(□)	(-)

In addition, for the NbTi and Nb3Sn superconductors, three parameters from input are used determine the fit to the critical properties:

• Maximum upper critical field	B_{c20m}	(T)
• Maximum critical temperature	T_{c20}	(K)

- Fitting constant for Jc C_0 (A T/m^2)

These parameters are adjusted for trimming the critical surface and properties to the desired superconductor.

Code Structure

The code consists mainly of a set of FORTRAN calling procedure and the actual optimisation procedures, also in FORTRAN. Note that the optimisation procedures can be called independently from the calling routines, if the cable optimisation is part of a more involved magnet optimisation procedure. The propers setting of the common areas and the call structure are described in the section on *Advanced Use*. The optimisation code needs to be linked to material properties routines. This section gives the description of each portion of *OPTICON*.

Main program

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

File Name	Usage
input file	Input of the design code and operating point. The user is prompted at the start of the run for the file name
`copper.scan`	history of the copper fraction optimisation
`helium.scan`	history of the helium (void) fraction optimisation
`Cu-nonCu.scan`	history of the Cu:Non-Cu ratio optimisation
terminal	Input of the user's selection from menu and interactive output
`opticon.log`	Output of the results

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 (and obviously units !) are respected and keeping in mind the requirements on the code efficiency. For the complete list of the property functions, please refer to the Solid and He_table manuals.

Input

The input to *OPTICON* consists of two stages. Firstly the operating point and design code must be input, to provide the optimiser with the necessary information. Following this, a menu driven interface is used to decide the *action* to be taken. The action can consist, as an example, in an optimisation, or in the calculation of the maximum allowable operating current density for the optimised cable. Optimised characteristics are retained throughout future actions, so that it is possible to change the operating point and check the effect on the allowable operating current density. In the next section the details of the paramater input are given. In the section following we discuss the menu options.

Parameters for operating point and design code

The following table contains the input parameters, their physical dimensions, default value and meaning for the *OPTICON* processor. The input is done using the FORTRAN instruction `NAMELIST`. The namelist is called `INDATA`. A sample input file is reported in the end of the manual.

Operating point

Variable	Type	Units	Default	Meaning
TOP	R	(K)	0.0	Operating temperature
BOP	R	(T)	0.0	Operating field
POP	R	(Pa)	0.0	Operating pressure
TAUDUM	R	(s)	0.0	Magnet discharge time
EPSLON	R	(-)	0.0	Operating strain on the superconductor
BDTMAX	R	(T/s)	0.0	Operating field change rate on the cable

Design limits

Variable	Type	Units	Default	Meaning
EMIN	R	(J/m^3)	0.0	Minimum energy margin (used as default)
DTMIN	R	(K)	0.0	Minimum temperature margin (used when the minimum energy margin is not given)
TMAX	R	(K)	0.0	Maximum hot-spot temperature during a quench
PMAX	R	(Pa)	0.0	Maximum hot-spot pressure during a quench

Cable characteristics

Variable	Type	Units	Default	Meaning
RRR	R	(-)	0.0	Stabilizer RRR
DSTRND	R	(m)	0.0	Strand diameter
CNCMAX	R	(-)	0.0	Maximum strand Cu:Non-Cu ratio to be used in the optimisation procedure. Additional copper can be used, but incorporated in the cable as co-wound strands. This copper will only be considered by the optimisation only in the quench limits, and not for stability
KP	R	(Pa)	0.0	Correction factor for the cable wetted perimeter. To be taken < 1, implies that a part of the surface of the strands is not in contact with the coolant (e.g. smashed strands)
CTHETA	R	(-)	0.0	Cosine of the average twisting angle of the strands in the cable. To be taken < 1, it implies that the strands are wound into the cable
LNORML	R	(m)	0.0	Normal length. Used in the determination oif the quench pressure, it must give an estimate for the final normal length (at the end of a quench). Taking the full cable length can result in a pessimistic limit
HTC	R	(W/m^2K)	0.0	Effective heat transfer coefficient at the strand surface. Used in the determination of the well-cooled regime
FRICTN	R	(-)	0.0	Average friction factor (used for the maximum pressure limit)

Cable fractions

Variable	Type	Units	Default	Meaning
FNC	R	(-)	0	Fraction of superconductor (non-copper) in the cable space cross section
FCU	R	(-)	0	Fraction of stabilizer (copper) in the cable space cross section
FHE	R	(-)	0	Fraction of coolant (helium) in the cable space cross section

Superconductors characteristics

Variable	Type	Units	Default	Meaning
ISC	I	(-)	0	Type of superconductor: (31) Standard NbTi (32) Standard Nb3Sn (<0) User's defined through the routine USERSC
TC0M	R	(K)	0	Critical temperature at zero field (for Nb_3Sn only)
BC20M	R	(T)	0	Critical field Bc2 at zero temperature (for Nb_3Sn only)
C0	R	(A T/m^2)	0	Scaling for critical current density Jc (for Nb_3Sn only)

Menu driven operations

The main menu of *OPTICON* is the following:

```
<<<   O P T I C O N   >>>
Enter Your Choice:
-----------------------------------------
( 1) ...... Input next data set
( 2) ...... Max Jcs for design
( 3) ...... Optimal fcu
( 4) ...... Optimal fcu+fhe
( 5) ...... Optimal fcu+fhe+max Cu:non-Cu

( 6) ...... Change operating point
( 7) ...... Change design
( 8) ...... Change limits
( 9) ...... Show data
(10) ...... Set options
-----------------------------------------
( 0) ...... END EXECUTION
```

The functions performed by the various choices are the following:

Option	*Action performed*
1	Input a new design. Note that as many design as desired can be appended on the same file. They are read in sequence each time that the input action is requested. An error message is issued in case of read error or end of the design data sets.
2	Compute the maximum allowable J in the cable space based on the current operating conditions, design code and cable fractions. This action is possible only if all design parameters are specified (including cable fractions). The present conditions and fractions can be either the result of the last read-in or of the last optimisation.
3	Optimise the copper fraction based on the current operating conditions, design code and helium cable fraction. This action is possible when all design parameters are specified up to the copper and non-copper fractions. The present operating conditions and design code is the result of the last read-in.
4	Optimise the helium and copper fraction based on the current operating conditions and design code. This action is possible when all design parameters are specified up to the cable fractions. The present operating conditions and design code is the result of the last read-in.
5	Optimise the helium and copper fraction scanning the maximum Cu:Non-Cu ratio, based on the current operating conditions and design code. The user is prompted for limits of the Cu:Non-Cu scan. This action is possible when all design parameters are specified up to the cable fractions and Cu:Non-Cu ratio. The present operating conditions and design code is the result of the last read-in.
6	Interactive setting of the operating point (keyboard input)
7	Interactive setting of the cable design parameters (keyboard input)

Option	*Action performed*
8	Interactive setting of the design limits (keyboard input)
9	Output the present design code, operating point and set options
10	Set options for operation (see later)

If the option **10** is chosen, a second menu is opened which toggles options on or off. The options that can be set are:

```
<<<     Set Options     >>>
Enter Your Choice:
------------------------------------------
( 1) ...... Fcu history
( 2) ...... Fcu+fhe history
( 3) ...... Fcu+fhe+max Cu:non-Cu history
( 4) ...... Detailed output
------------------------------------------
( 0) ...... Return to previous menu
------------------------------------------
```

The function of each of them is the following:

Option	*Action performed*
1	Toggle on/off the history of the copper fraction optimization
2	Toggle on/off the history of the helium and copper fraction optimization
3	Toggle on/off the history of the helium and copper fraction optimization with Cu:Non-Cu scan
4	Toggle on/off the detailed output of design code and operating point on the terminal at the end of each action

Note that you can see the choices in force with the option **9** (Show data) in the main menu.

External Routines

A single external routine is provided to the user, included as a dummy in the file **`opticon.f`**, to be able to specify the critical properties of an arbitrary superconductor. This routine is called only in the case that the parameter ISC in the input namelist is set to a negative number.

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

```
SUBROUTINE USERSC (TOP   ,BOP   ,EPSLON,TCS   ,TC    ,
                   JC    ,JNONCU)
```

Compute the critical properties of a superconductor.

List of variables:

Variable	Type	I/O	Units	Meaning
TOP	R	I	(K)	Operating temperature
BOP	R	I	(T)	Operating field
EPSLON	R	I	(-)	Operating strain
TCS	R	I	(K)	Requested current sharing temperature for stability (note that this is an INPUT to the routine)
JC	R	O	(A/m^2)	Critical current density at the operating conditions
TC	R	O	(K)	Critical temperature at the operating conditions
JNONCU	R	O	(A/m^2)	Critical current density at the operating conditions of field and strain that gives the specified current sharing temperature TCS. This is in general JC(TCS,BOP,EPSLON)

Errors

No detailed error control is performed by OPTICON. A limited number of checks are done on the input data for the operating point and design code, and the requested action from the menu. In case that an input data is not correct or a requested action is not possible, the following message is issued by the program:

```
Requested action is not possible. Input incomplete
or incorrect. <Return> to continue
```

The user must check the input data or the requested menu action.

Advanced Use

The set of routines in `opticon.f` is thought also for use in an external optimisation loop, regardin, as an example, a global magnet or cost optimisation. All menu actions elencated above correspond to a single routine, that can be called separately. For inclusion in a procedure the details of the calls must be respected. In the following section the details of the calling parameters and the communication of data to a routine are given.

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

Commons

Two commons exchange design (`DESIGN`) and superconductor (`SUPERK`) data with all routines. They are described in the call procedure of each routine (see next sections). In addition, the following commons, present in all routines, govern the level of output and its allocation:

```
C * Flags for optional outputs
       LOGICAL HISTR1,HISTR2,HISTR3,DETAIL
       COMMON/OUTMOR/HISTR1,HISTR2,HISTR3,DETAIL
```

each of the logical above, when `.true.`, causes detailed output of :

`HISTR1`	copper fraction optimisation history
`HISTR2`	helium fraction optimisation history
`HISTR3`	Cu:Non-Cu ratio scan history

Finally, the following common allows debugging to take place, at various levels of details, printing the results of intermediate steps:

```
       INTEGER IDEBUG
       COMMON/DEBUGC/IDEBUG
```

The variable `IDEBUG` should be set to 0 for no debug to take place. See the code listing for more details.

Allowable cable space operating current density

```
C #####################################################################
      SUBROUTINE OPT_J (TOP   ,BOP   ,POP   ,TAUDUM,EPSLON,BDTMAX,
     &                  RRR   ,FHE   ,FST   ,FNC   ,FCU   ,CNCMAX,
     &                  DSTRND,KP    ,LNORML,HTC   ,EMIN  ,DTMIN ,
     &                  IMARGN,TMAX  ,PMAX  ,JMAX  ,FCUSTR,JC    ,
     &                  TC    ,TCS   ,EMAR  ,LIMIT )
C #####################################################################
C #
C # This subroutine optimizes the cable space current density at the
C # operating conditions given and for a cable design, with:
C #
C #  -) guaranteed minimum stability (or temperature) margin
C #  -) operation in the well-cooled regime
C #  -) limited hot spot temperature
C #  -) limited maximum quench pressure
C #  -) limits on the saturation of the outer filaments at given dB/dt
C #                            (this last is a dummy for the moment)
C #
C # Input variables:
C #
C # TOP      (K)  Operating helium temperature
C # BOP      (T)  Operating magnetic field
C # POP     (Pa)  Operating pressure
C # TAUDUM   (s)  Minimum dump time constant, depending on the maximum
C #               permissible voltage at the coil terminals
C # EPSLON   (-)  Operating longitudinal strain in superconductor
C # BDTMAX (T/s)  Operating maximum field change rate
C # RRR      (-)  Copper residual resistivity ratio at B=0
C # FHE      (-)  Fraction of helium in the cable space
C # FST      (-)  Fraction of strands in the cable space. Generally for
C #               consistence FST = (1-FHE) (must be set !)
C # FNC       (-) Fraction of non-copper in the cable space
C # FCU       (-) Fraction of copper in the cable space. Generally for
C #               consistence FCU=FST-FNC
C # CNCMAX   (-)  Limit on the copper:non-copper ratio in the strand
C # DSTRND   (m)  Strand diameter
C # KP       (-)  Correction factor for wetted area (effect of contacts)
C # LNORML   (m)  Normal length (at the end of the dump)
C # HTC  (W/m2K)  Heat transfer coefficient
C # EMIN  (J/m3)  Minimum energy margin
C # DTMIN    (K)  Minimum temperature margin
C # IMARGN   (-)  Flag signaling the use of energy or temperature margin
C #                  1      Energy margin (EMIN must be given !)
C #                  2      Temperatre margin (DTMIN must be given !)
C # TMAX     (K)  Maximum hot-spot temperature
C # PMAX    (Pa)  Maximum hot-spot pressure
C #
C # Ouput variables:
C #
C # JMAX  (A/mm2) Maximum operating cable space current density
C #
C # FCUSTR    (-) Fraction of copper in the strand (may be < FCU)
C # JC    (A/mm2) Critical non-copper current density
C # TC        (K) Critical temperature
C # TCS       (K) Current sharing temperature
C # EMAR  (mJ/cc) Actual energy margin for the cable (estimated)
C # LIMIT     (-) Character indicating the most restrictive limit
C #
C # The following parameters are to be set according to the design code.
C # They are passed through the commons DESIGN (and SUPERK for the Nb3Sn
C # constants Tc0m, Bc20m and C0 used in the L.Summer's expressions)
C #
C # ISC      (-)  Superconductor type:  31  standard NbTi
C #                                     32  standard Nb3Sn
C #                                     <0  user's defined superconductor
C # CTHETA   (-)  Cosine of the average twisting angle
C # FRICTN   (-)  Average friction factor for the helium expulsion
C #
C #    The following are Nb3Sn parameters (used only if ISC=32)
C #
C # TC0M     (K)  Tc for Nb3Sn at 0 field and strain
C # BC20M    (T)  Bc for Nb3Sn at 0 temperature and strain
C # C0 (AT/m**2)  Scaling constant for Jc for Nb3Sn
C #
C #####################################################################
```

Copper fraction optimisation

```
C ######################################################################
      SUBROUTINE OPT_CU(TOP   ,BOP   ,POP   ,TAUDUM,EPSLON,BDTMAX,
     &                  RRR   ,FHE   ,FST   ,CNCMAX,DSTRND,KP    ,
     &                  LNORML,HTC   ,EMIN  ,DTMIN ,IMARGN,TMAX  ,
     &                  PMAX  ,JMAX  ,FNC   ,FCU   ,FCUSTR,JC    ,
     &                  TC    ,TCS   ,EMAR  ,LIMIT )
C ######################################################################
C #
C # This subroutine optimizes the cable copper fraction in order to
C # achieve the maximum allowable cable space current density at the
C # operating conditions given, with:
C #
C #  -) guaranteed minimum stability (or temperature) margin
C #  -) operation in the well-cooled regime
C #  -) limited hot spot temperature
C #  -) limited maximum quench pressure
C #  -) limits on the saturation of the outer filaments at given dB/dt
C #                              (this last is a dummy for the moment)
C #
C # This is done performing a forward search on the copper fraction
C #
C # Input variables:
C #
C # TOP      (K)  Operating helium temperature
C # BOP      (T)  Operating magnetic field
C # POP     (Pa)  Operating pressure
C # TAUDUM   (s)  Minimum dump time constant, depending on the maximum
C #               permissible voltage at the coil terminals
C # EPSLON   (-)  Operating longitudinal strain in superconductor
C # BDTMAX (T/s)  Operating maximum field change rate
C # RRR      (-)  Copper residual resistivity ratio at B=0
C # FHE      (-)  Fraction of helium in the cable space
C # FST      (-)  Fraction of strands in the cable space. Generally for
C #               consistence FST = (1-FHE) (must be set !)
C # CNCMAX   (-)  Limit on the copper:non-copper ratio in the strand
C # DSTRND   (m)  Strand diameter
C # KP       (-)  Correction factor for wetted area (effect of contacts)
C # LNORML   (m)  Normal length (at the end of the dump)
C # HTC  (W/m2K)  Heat transfer coefficient
C # EMIN  (J/m3)  Minimum energy margin
C # DTMIN    (K)  Minimum temperature margin
C # IMARGN   (-)  Flag signaling the use of energy or temperature margin
C #                  1      Energy margin (EMIN must be given !)
C #                  2      Temperatre margin (DTMIN must be given !)
C # TMAX     (K)  Maximum hot-spot temperature
C # PMAX    (Pa)  Maximum hot-spot pressure
C #
C # Ouput variables:
C #
C # JMAX  (A/mm2) Maximum operating cable space current density
C #
C # FNC       (-) Fraction of non-copper in the cable space
C # FCU       (-) Fraction of copper in the cable space
C # FCUSTR    (-) Fraction of copper in the strand (may be < FCU)
C # JC    (A/mm2) Critical non-copper current density
C # TC        (K) Critical temperature
C # TCS       (K) Current sharing temperature
C # EMAR  (mJ/cc) Actual energy margin for the cable (estimated)
C # LIMIT     (-) Character indicating the most restrictive limit
C #
C # The following parameters are to be set according to the design code.
C # They are passed through the commons DESIGN (and SUPERK for the Nb3Sn
C # constants Tc0m, Bc20m and C0 used in the L.Summer's expressions)
C #
C # ISC      (-)  Superconductor type:  31  standard NbTi
C #                                     32  standard Nb3Sn
C #                                     <0  user's defined superconductor
C # CTHETA   (-)  Cosine of the average twisting angle
C # FRICTN   (-)  Average friction factor for the helium expulsion
C #
C #    The following are Nb3Sn parameters (used only if ISC=32)
C #
C # TC0M     (K)  Tc for Nb3Sn at 0 field and strain
C # BC20M    (T)  Bc for Nb3Sn at 0 temperature and strain
C # C0 (AT/m**2)  Scaling constant for Jc for Nb3Sn
C #
C ######################################################################
```

Copper and helium fraction optimisation

```
C ####################################################################
      SUBROUTINE OPT_HE(TOP   ,BOP   ,POP   ,TAUDUM,EPSLON,BDTMAX,
     &                  RRR   ,CNCMAX,DSTRND,KP    ,LNORML,HTC   ,
     &                  EMIN  ,DTMIN ,IMARGN,TMAX  ,PMAX  ,JMAX  ,
     &                  FHE   ,FST   ,FNC   ,FCU   ,FCUSTR,JC    ,
     &                  TC    ,TCS   ,EMAR  ,LIMIT )
C ####################################################################
C #
C # This subroutine optimizes the cable fractions (He, Cu, NC) in order
C # to achieve the maximum allowable cable space current density at the
C # operating conditions given, with:
C #
C #  -) guaranteed minimum stability (or temperature) margin
C #  -) operation in the well-cooled regime
C #  -) limited hot spot temperature
C #  -) limited maximum quench pressure
C #  -) limits on the saturation of the outer filaments at given dB/dt
C #                              (this last is a dummy for the moment)
C #
C # This is done performing a forward search on the helium fraction
C # and an optimum copper fraction search at each step
C #
C # Input variables:
C #
C # TOP      (K)  Operating helium temperature
C # BOP      (T)  Operating magnetic field
C # POP     (Pa)  Operating pressure
C # TAUDUM   (s)  Minimum dump time constant, depending on the maximum
C #               permissible voltage at the coil terminals
C # EPSLON   (-)  Operating longitudinal strain in superconductor
C # BDTMAX (T/s)  Operating maximum field change rate
C # RRR      (-)  Copper residual resistivity ratio at B=0
C # CNCMAX   (-)  Limit on the copper:non-copper ratio in the strand
C # DSTRND   (m)  Strand diameter
C # KP       (-)  Correction factor for wetted area (effect of contacts)
C # LNORML   (m)  Normal length (at the end of the dump)
C # HTC  (W/m2K)  Heat transfer coefficient
C # EMIN  (J/m3)  Minimum energy margin
C # DTMIN    (K)  Minimum temperature margin
C # IMARGN   (-)  Flag signaling the use of energy or temperature margin
C #                  1      Energy margin (EMIN must be given !)
C #                  2      Temperatre margin (DTMIN must be given !)
C # TMAX     (K)  Maximum hot-spot temperature
C # PMAX    (Pa)  Maximum hot-spot pressure
C #
C # Ouput variables:
C #
C # JMAX  (A/mm2) Maximum operating cable space current density
C #
C # FHE      (-)  Fraction of helium in the cable space
C # FST      (-)  Fraction of strands in the cable space
C # FNC       (-) Fraction of non-copper in the cable space
C # FCU       (-) Fraction of copper in the cable space
C # FCUSTR    (-) Fraction of copper in the strand (may be < FCU)
C # JC    (A/mm2) Critical non-copper current density
C # TC        (K) Critical temperature
C # TCS       (K) Current sharing temperature
C # EMAR  (mJ/cc) Actual energy margin for the cable (estimated)
C # LIMIT     (-) Character indicating the most restrictive limit
C #
C # The following parameters are to be set according to the design code.
C # They are passed through the commons DESIGN (and SUPERK for the Nb3Sn
C # constants Tc0m, Bc20m and C0 used in the L.Summer's expressions)
C #
C # ISC      (-)  Superconductor type:  31  standard NbTi
C #                                     32  standard Nb3Sn
C #                                     <0  user's defined superconductor
C # CTHETA   (-)  Cosine of the average twisting angle
C # FRICTN   (-)  Average friction factor for the helium expulsion
C #
C #    The following are Nb3Sn parameters (used only if ISC=32)
C #
C # TC0M     (K)  Tc for Nb3Sn at 0 field and strain
C # BC20M    (T)  Bc for Nb3Sn at 0 temperature and strain
C # C0 (AT/m**2)  Scaling constant for Jc for Nb3Sn
C #
C ####################################################################
```

Copper and helium fraction optimisation with Cu:Non-Cu scan

```
C ######################################################################
      SUBROUTINE OPT_CN(TOP   ,BOP   ,POP   ,TAUDUM,EPSLON,BDTMAX,
     &                  RRR   ,DSTRND,KP    ,LNORML,HTC   ,EMIN  ,
     &                  DTMIN ,IMARGN,TMAX  ,PMAX  ,CNCLOW,CNCUPP,
     &                  JMAX  ,CNCMAX,FHE   ,FST   ,FNC   ,FCU   ,
     &                  FCUSTR,JC    ,TC    ,TCS   ,EMAR  ,LIMIT )
C ######################################################################
C #
C # This subroutine optimizes the cable fractions (He, Cu, NC) and the
C # max Cu:non-Cu ratio in order to achieve the maximum allowable cable
C # space current density at the operating conditions given, with:
C #
C #  -) guaranteed minimum stability (or temperature) margin
C #  -) operation in the well-cooled regime
C #  -) limited hot spot temperature
C #  -) limited maximum quench pressure
C #  -) limits on the saturation of the outer filaments at given dB/dt
C #                             (this last is a dummy for the moment)
C #
C # This is done performing a forward search on the max Cu:non-Cu ratio
C # and an optimum helium fraction search at each step.
C #
C # Input variables:
C #
C # TOP      (K)  Operating helium temperature
C # BOP      (T)  Operating magnetic field
C # POP     (Pa)  Operating pressure
C # TAUDUM   (s)  Minimum dump time constant, depending on the maximum
C #               permissible voltage at the coil terminals
C # EPSLON   (-)  Operating longitudinal strain in superconductor
C # BDTMAX (T/s)  Operating maximum field change rate
C # RRR      (-)  Copper residual resistivity ratio at B=0
C # DSTRND   (m)  Strand diameter
C # KP       (-)  Correction factor for wetted area (effect of contacts)
C # LNORML   (m)  Normal length (at the end of the dump)
C # HTC  (W/m2K)  Heat transfer coefficient
C # EMIN  (J/m3)  Minimum energy margin
C # DTMIN    (K)  Minimum temperature margin
C # IMARGN   (-)  Flag signaling the use of energy or temperature margin
C #                  1      Energy margin (EMIN must be given !)
C #                  2      Temperatre margin (DTMIN must be given !)
C # TMAX     (K)  Maximum hot-spot temperature
C # PMAX    (Pa)  Maximum hot-spot pressure
C # CNCLOW   (-)  Lower boundary for maximum strand Cu:non-Cu ratio
C # CNCUPP   (-)  Upper boundary for maximum strand Cu:non-Cu ratio
C #
C # Ouput variables:
C #
C # JMAX  (A/mm2) Maximum operating cable space current density
C #
C # CNCMAX   (-)  Limit on the copper:non-copper ratio in the strand
C # FHE      (-)  Fraction of helium in the cable space
C # FST      (-)  Fraction of strands in the cable space
C # FNC       (-) Fraction of non-copper in the cable space
C # FCU       (-) Fraction of copper in the cable space
C # FCUSTR    (-) Fraction of copper in the strand (may be < FCU)
C # JC    (A/mm2) Critical non-copper current density
C # TC        (K) Critical temperature
C # TCS       (K) Current sharing temperature
C # EMAR  (mJ/cc) Actual energy margin for the cable (estimated)
C # LIMIT     (-) Character indicating the most restrictive limit
C #
C # The following parameters are to be set according to the design code.
C # They are passed through the commons DESIGN (and SUPERK for the Nb3Sn
C # constants Tc0m, Bc20m and C0 used in the L.Summer's expressions)
C #
C # ISC      (-)  Superconductor type:  31  standard NbTi
C #                                     32  standard Nb3Sn
C #                                     <0  user's defined superconductor
C # CTHETA   (-)  Cosine of the average twisting angle
C # FRICTN   (-)  Average friction factor for the helium expulsion
C #
C #    The following are Nb3Sn parameters (used only if ISC=32)
C #
C # TC0M     (K)  Tc for Nb3Sn at 0 field and strain
C # BC20M    (T)  Bc for Nb3Sn at 0 temperature and strain
C # C0 (AT/m**2)  Scaling constant for Jc for Nb3Sn
C #
C ######################################################################
```

References

[1] L.Bottura, *Stability, Protection and AC Loss of Cable-in-Conduit Conductors. A Designer's Approach*, Fus. Eng. Des., **20**, 351-362, 1992.

Examples

Here an example of the use of *OPTICON* is given. The following section gives the file containing the design parameters (operating point and design code). Note how the first namelist is giving all details, while the following ones are just changing the operating point (they will be used to explore the allowable cable space operating current density).

Input for the Design Parameters

```
Test Run for the manual
&INDATA
  TOP   =    4.5, BOP   =   12.0, POP   = 10.0E5, TAUDUM=   15.0,
  EPSLON= -0.005, BDTMAX=    1.0,

  FNC   =    0.2, FCU   =    0.4, FHE   =    0.4,

  EMIN  =  500E3, DTMIN =    0.0, TMAX  =  231.0, PMAX  =  200E5,

  RRR   =  100.0, CNCMAX=    2.0, DSTRND= 0.8E-3, KP    =0.66667,
  LNORML=   50.0, HTC   =  600.0, CTHETA=   0.93, FRICTN=  0.010,

  ISC   =     32,
  TC0M  =   18.0, BC20M =   28.0, C0    =1.16E10,

 /
 &INDATA
  TOP   =    4.5, BOP   =   13.0,
 /
 &INDATA
  TOP   =    5.5,
 /
 &INDATA
  TOP   =    6.5,
 /
```

Menu actions

In the interactive run the following responses are given to the menu:

response	*action performed*
1	input the new design. Note that in the design definition the initial cable fractions are given. This allows the next action.
2	compute the maximum allowable J in the cable space based on the input cable fractions
3	optimise the copper fraction at the present operating conditions and design code. This action changes the copper fraction
1	input a new design. According to the file given above, this only modifies the operating field from 12 T to 13 T (the operating temperature given is the same as before). All other parameters, including the optimised copper fraction, are retained
2	compute the maximum allowable J in the cable space based on the new operating conditions
1	input a new design. This changes the operating temperature only from 4.5 K to 5.5 K
2	compute the maximum allowable J in the cable space based on the new operating conditions
1	input a new design. This changes the operating temperature only from 5.5 K to 6.5 K
2	compute the maximum allowable J in the cable space based on the new operating conditions
0	end execution

Results

These are the results of the actions performed above with the input data set given (note that menu printings and minor messages have been skipped):

```
-----------------------------------------------
Maximum allowable cable space current density
-----------------------------------------------
         Operating Conditions
Operating temperature........  4.50000E+00 (K)
Operating field..............  1.20000E+01 (T)
Operating pressure...........  1.00000E+06 (Pa)
Discharge time constant......  1.50000E+01 (s)
Operating strain............. -5.00000E-03 (-)
Operating dB/dt..............  1.00000E+00 (T/s)
                 Cable design
Helium (void) fraction.......  4.00000E-01 (-)
Strand fraction..............  6.00000E-01 (-)
Non-copper fraction..........  2.00000E-01 (-)
Copper fraction in cable.....  4.00000E-01 (-)
Copper fraction in strand....  4.00000E-01 (-)
Strand Cu:non-CU ratio.......  2.00000E+00 (-)
Cable Cu:non-CU ratio........  2.00000E+00 (-)

Cable space J................  5.03414E+01 (A/mm**2)
Critical (non-copper) J......  5.10625E+02 (A/mm**2)
Critical temperature.........  1.07117E+01 (K)
Current sharing temperature..  6.95793E+00 (K)
Energy margin................  7.48387E+02 (mJ/cm**3)
Temperature margin...........  2.45793E+00 (K)
Limited by:
hot-spot temperature

-----------------------------------------------
Copper fraction optimisation
-----------------------------------------------
         Operating Conditions
Operating temperature........  4.50000E+00 (K)
Operating field..............  1.20000E+01 (T)
Operating pressure...........  1.00000E+06 (Pa)
Discharge time constant......  1.50000E+01 (s)
Operating strain............. -5.00000E-03 (-)
Operating dB/dt..............  1.00000E+00 (T/s)
                 Cable design
Helium (void) fraction.......  4.00000E-01 (-)
Strand fraction..............  6.00000E-01 (-)
Non-copper fraction..........  1.75758E-01 (-)
Copper fraction in cable.....  4.24242E-01 (-)
Copper fraction in strand....  3.51515E-01 (-)
Strand Cu:non-CU ratio.......  2.00000E+00 (-)
Cable Cu:non-CU ratio........  2.41379E+00 (-)

Cable space J................  5.18444E+01 (A/mm**2)
Critical (non-copper) J......  5.10625E+02 (A/mm**2)
Critical temperature.........  1.07117E+01 (K)
Current sharing temperature..  6.31264E+00 (K)
Energy margin................  5.51909E+02 (mJ/cm**3)
Temperature margin...........  1.81264E+00 (K)
Limited by:
hot-spot temperature
```

(continued)

```
-----------------------------------------------
Maximum allowable cable space current density
-----------------------------------------------
         Operating Conditions
Operating temperature........  4.50000E+00 (K)
Operating field.............  1.30000E+01 (T)
Operating pressure...........  1.00000E+06 (Pa)
Discharge time constant......  1.50000E+01 (s)
Operating strain............ -5.00000E-03 (-)
Operating dB/dt.............  1.00000E+00 (T/s)
                Cable design
Helium (void) fraction.......  4.00000E-01 (-)
Strand fraction.............  6.00000E-01 (-)
Non-copper fraction..........  1.75758E-01 (-)
Copper fraction in cable.....  4.24242E-01 (-)
Copper fraction in strand....  3.51515E-01 (-)
Strand Cu:non-CU ratio.......  2.00000E+00 (-)
Cable Cu:non-CU ratio........  2.41379E+00 (-)

Cable space J...............  3.86496E+01 (A/mm**2)
Critical (non-copper) J......  3.93540E+02 (A/mm**2)
Critical temperature.........  1.01268E+01 (K)
Current sharing temperature..  6.14215E+00 (K)
Energy margin...............  5.00000E+02 (mJ/cm**3)
Temperature margin...........  1.64215E+00 (K)
Limited by:
well-cooled operation

-----------------------------------------------
Maximum allowable cable space current density
-----------------------------------------------
         Operating Conditions
Operating temperature........  5.50000E+00 (K)
Operating field.............  1.30000E+01 (T)
Operating pressure...........  1.00000E+06 (Pa)
Discharge time constant......  1.50000E+01 (s)
Operating strain............ -5.00000E-03 (-)
Operating dB/dt.............  1.00000E+00 (T/s)
                Cable design
Helium (void) fraction.......  4.00000E-01 (-)
Strand fraction.............  6.00000E-01 (-)
Non-copper fraction..........  1.75758E-01 (-)
Copper fraction in cable.....  4.24242E-01 (-)
Copper fraction in strand....  3.51515E-01 (-)
Strand Cu:non-CU ratio.......  2.00000E+00 (-)
Cable Cu:non-CU ratio........  2.41379E+00 (-)

Cable space J...............  2.20716E+01 (A/mm**2)
Critical (non-copper) J......  2.97891E+02 (A/mm**2)
Critical temperature.........  1.01268E+01 (K)
Current sharing temperature..  7.27991E+00 (K)
Energy margin...............  5.00000E+02 (mJ/cm**3)
Temperature margin...........  1.77991E+00 (K)
Limited by:
well-cooled operation
```