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EIG — An Input Generator for EFFI

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KERNFORSCHUNGSZENTRUM KARLSRUHE

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Abstract

The EFFI-code allows to calculate electromagnetic fields, forces and inductances for ironless magnetic systems of arbitrary geometry. The input for EFFI consists either of complete circles (LOOP) and/or circular arcs (ARC) and/or straight sections (GCE). So, even modestly complex coils give rise to lengthly EFFI input files. To ease life, the EFFI input generator (EIG) writes the input file for EFFI. The generator contains several families of coil shapes, each coil being characterized by several geometrical and electrical parameters. The coils and the meaning of the parameters are described and visualized.

Zusammenfassung

EIG - Ein Input-Generator für EFFI

Das EFFI-Programm erlaubt die Berechnung elektromagnetischer Felder, Kräfte und Induktivitäten für eisenlose Magnetsysteme willkürlicher Geometrie. Die EFFI-Eingabe besteht entweder aus vollständigen Kreisen (LOOP) und/oder Kreisbogenstücken (ARC) und/oder geraden Stücken. Daher geben bereits relativ einfache Spulen zu länglicher Eingabe Veranlassung. Zur Erleichterung schreibt der EFFI-Eingabe-Generator (EIG) die Eingabe für EFFI. Im Generator sind mehrere Spulenfamilien beschrieben; jede Spule ist durch mehrere geometrische und elektrische Parameter charakterisiert. Die Spulen und die Bedeutung ihrer Parameter sind beschrieben.

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1. Introduction

EFFI /1/ calculates electromagnetic fields, forces and inductances for magnetic systems of arbitrary geometry without iron. Any current carrying coils which are input to EFFI are out of complete circles (LOOP), circular arcs (ARC) and straight sections (GCE). Therefore, even modestly complex coils give rise to lengthly EFFI input files. To ease life, the EFFI Input Generator (EIG) writes the input file for EFFI. The generator contains several families of coil shapes, each being characterized by several geometrical and electrical parameters. EIG is supported by several graphics codes (e. g. OHLGA, SAMPP, and FEMVIEW), so that the user can produce pictures of the coils to prove whether the input is right or not.

In addition to creating these special coil shapes, EIG can rotate and translate the coils. Especially with force calculations, the input generator is a big help.

The code we describe is the result of some versions of different input generators implemented at various computer centers and changed by the users. A handwritten copy of Brad Johnston from LLNL of a special input generator, a collection of pictures and calculations made in Madison, Wisconsin, and pictures created by a IBM-Graphic System supported by calculations on an IBM-computer in KfK, Karlsruhe, are the basis of this description. It should be mentioned, that the coils described in this input generator are "mirror-related". An input generator for tokamak related magnet systems (TOKEF) is implemented in Karlsruhe. The description will be published soon.

/1/ UCID 17621 "EFFI - a code for calculating the electromagnetic field, force, and inductance in coil systems of arbitrary geometry" by S. J. Sackett, 1977.

2. Structure of the EIG

It is assumed here that the reader is somewhat familiar with EFFI input. Recall that EFFI input consists of three parts. These parts are shown below:

Title card units data parameter data	Part 1
$	
Coil geometry and current data	Part 2
$	
Output data	Part 3
$	

The output of EIG is just such a file. The EIG input also consists of the three basic parts /2/. For EIG the dollar signs "$", are replaced by three stars, *** . Other than this, the first and third parts of the EIG input are exactly the same as the corresponding EFFI input. Only the second part is different, and it is quite different. In EFFI only three current carrying geometries are allowed, They are GCE for general current element, which is a straight section, LOOP for a complete circular loop and ARC for a circular one. All these have rectangular cross sections. In the second part of the EFFI input, any of these three names is followed by a number of parameters which characterize the element geometry and give the current density. The second part of the EIG input consists of the coil names in the list in the next chapter along with these parameters. The job of EIG is mainly to convert these more comples shapes into a number of the simpler EFFI elements.

We give an example of ying-yang input to EFFI. The first step is to set up the EIG input. This file is given below:

```
example of yy input
***
COIL = test $
YY 10. 2. 5. 8. 3. 1. 1.E7 $
***
ZXY 0.  .5 15. 0.  .5  10. 0.  5  1  $
***
```

/2/ For force calculations, there can be four parts, see below.

A check on the meaning of the YY parameters shows that

major radius = 10 m
minor radius = 2 m
the mouth opening = 5 m
distance of center of coils to origin = 8 m
the cross section is 3 m x 1 m
the current density is $10^7 \cdot A/m^2$

In the ZXY-grid the positions are specified where the field values should been calculated.

An operationel chart on the execution of the program is:

EIG input
↓
EIG
↓
EFFI input

The output of EIG is a file ready to go as input to EFFI.

Note:

The input of the coil geometry and current data for EIG is different in Livermore and Karlsruhe:

Livermore Input:

line 1 COIL = name, $

line 2 coil type, coil data, $

Karlsruhe Input:

line 1 COIL = name

line 2 coil type

line 3 number of input data

line 4 coil data

3. Rotation and Translation of Coils

3.1 Rotation of Coils

Rotation is specified by a point Q (Q_X, Q_Y, Q_Z) about which a coil is to be rotated by three Euler angles α_Q, β_Q, γ_Q.

Euler Angles

The Euler angle convention used in EFFI is Z-X-Z'. By this is meant to rotate by an angle α about the z-axis, then by an angle β about the new X-axis, and last by an angle γ about the new Z-axis; this is illustrated in Fig. 3.1-1:

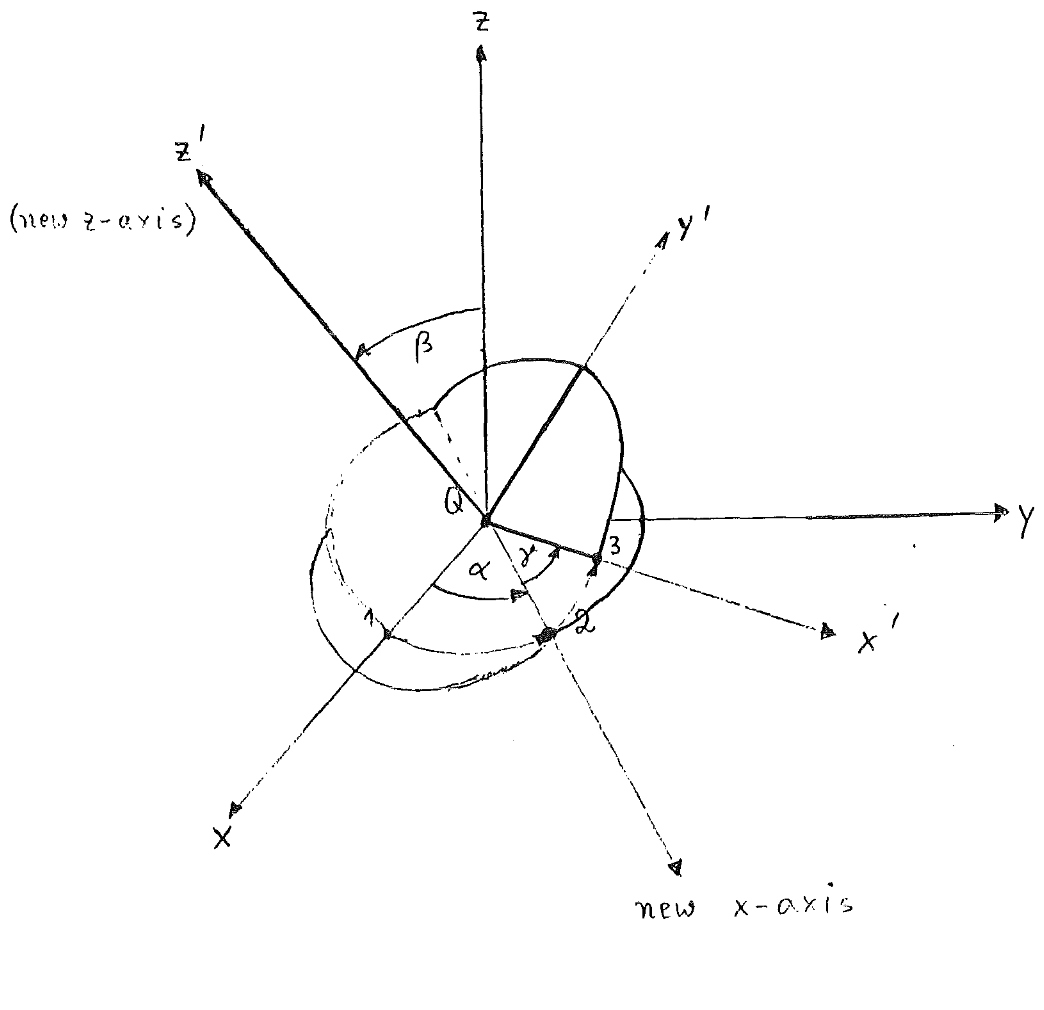


Fig. 3.1-1: EULER angles α, β, γ.

From Fig. 3.1-1 one can see that the original X-axis hits the horizontal circle (the original X-Y plane) at point 1. The first Euler angle α about the Z-axis moves the X-axis to point 2. The second Euler angle rotation is about this new X-axis through point 2 and moves the original Z-axis from Z to Z'. Lastly we rotate by the angle γ about the Z'-axis and move the X-axis from point 2 to point 3.

A few examples may help the reader. If the original system is the first figure in Fig. 3.1-2, the second and third one as indicated.

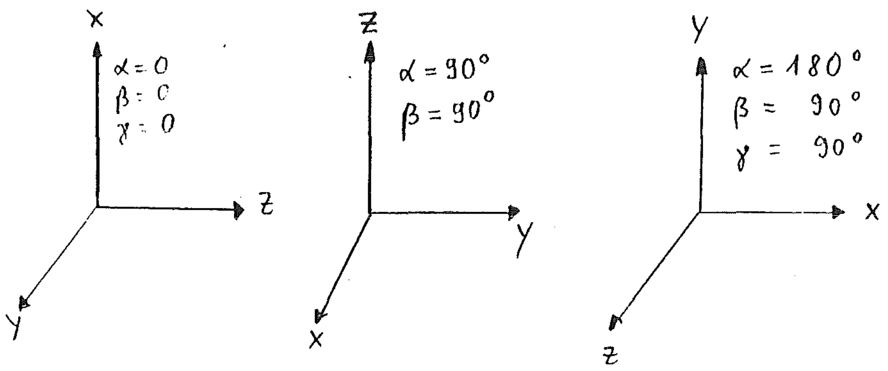


Fig. 3.1-2: Example for rotation.

Example for rotation

Suppose one wishes to rotate a YYP coil by 90^0 about the Y-axis. The point Q would be the origin (0., 0., 0.) and the corresponding Euler angles are α = 90, β = 90, γ = -90.

The EIG input is as follows:

```
EXAMPLE OF ROTATION
***
YYP  10.  2.  5.  8.  3.  1.  1.E7
      0.  0.  0. 90. 90. -90.  $
***
XYZ   0.  1. 10.  0.  1. 10.  0.  15 1 $
***
```

Notice that the dollar sign, $, which is usually at the end of the coil description parameters has been moved after the rotation values.

3.2 Translation of Coils

Translation is specified by a displacement Δx, Δy, Δz (three examples).

For example, if one wished to move the YYP by .1 m in the X-direction, .2 m in the Y-direction and .3 m in the Z-direction the input would be:

```
EXAMPLE OF TRANSLATION
***
YYP  10.  2.  5.  8.  3.  1.  1.E7
     .1   .2  .3  $
***
XYZ   0.  1.  10.  0.  1.  10.  0.  15 1 $
***
```

Notice that the dollar sign, $, which is usually at the end of the coil description parameters has been moved after the translation values.

3.3 Combination of Rotation and Translation

It is also possible to combine a coil rotation and translation. The translation follows the rotation. If we wished to combine the previous transformations, the EIG input would be as follows:

```
EXAMPLE OF ROTATION AND TRANSLATION

***
YYP  10.  2.  5.  8.  3.  1.  1.E7
      0.  0.  0.  90.  90.  -90.  .1  .2  .3  ∅
***
XYZ   0.  1.  10.  0.  1.  10.  0.  15  1 ∅
***
```

Rotation and/or translation is possible for all coils of the input generator implemented in KfK, Karlsruhe.

3.4 Description of the Transformation

Given a global cartesian coordinate system x, y, z, let a second system x', y', z' be defined by the EULER rotation angles α, β, γ. If a vector ξ is given in the global system and the vector ξ' is its image in the rotated system (i. e. ξ' is where ξ rotates with the x', y', z' system) then the components of ξ' in the global system are given by /2/.

$$\xi' = M \cdot \xi$$

where:

$$M = A_z(\alpha)\, A_x(\beta)\, A_z(\gamma), \text{ and}$$

$$A_x(\theta) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{pmatrix}$$

$$A_z(\theta) = \begin{pmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

/2/ H. GOLDSTEIN, Classical Mechanics, 1950, p. 107.

Next, suppose $\bar{P}$ is a point in the global system, with respect to which a local coordinate system x', y', z' is defined by the three EULER angles α_p, β_p, γ_p. (see Fig. 3.4-1)

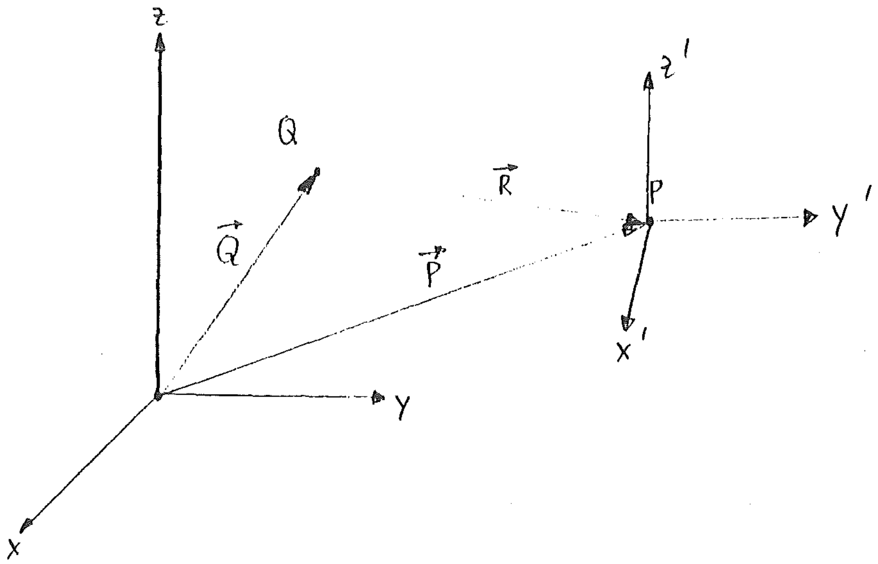


Fig. 3.4-1: Coordinate Systems

We wish to perform an EULER angle rotation of the local system at $\bar{P}$ rigidly about a point $\bar{Q}$ using the EULER angles α, β, γ. Let $\bar{i}_L$, $\bar{j}_L$, $\bar{k}_L$ be the local unit vectors at P (corresponding to α_p, β_p, γ_p). Let $\bar{R}$ be the vector from $\bar{Q}$ to $\bar{P}$, so that $\bar{R} = \bar{P} - \bar{Q}$.

Define the vectors $\bar{A}$, $\bar{B}$, $\bar{C}$, such that

$$\bar{A} = \bar{R} + \bar{i}_L$$
$$\bar{B} = \bar{R} + \bar{j}_L$$
$$\bar{C} = \bar{R} + \bar{k}_L$$

Now rotate $\bar{R}$, $\bar{A}$, $\bar{B}$, and $\bar{C}$ about Q with respect to the EULER angles α, β, γ. The result is:

$$\bar{R}' = MR$$
$$\bar{A}' = MA = M(\bar{R} + \bar{i}_L) = MR + M\bar{L}_L = \bar{R}' + M\bar{i}_L$$
$$\bar{B}' = \bar{R}' + M\bar{j}_L$$
$$\bar{C}' = \bar{R} + M\bar{k}_L$$
$$\bar{P}' = \bar{Q} + \bar{R}'$$

Let $\overline{i'_L}$, $\overline{j'_L}$, $\overline{k'_L}$ be the transformed local unit vectors of $\bar{P}'$. Then $\bar{A}' = \bar{R}' + \overline{i'_L}$, so that

$$\overline{i'_L} = \bar{A}' - \bar{R}' = M\overline{i_L}$$

In the same way

$$j'_L = M\overline{j_L}$$
$$k'_L = M\overline{k_L}$$

In order to go back and forth between the local system at P and the rotated system at P', we need to solve the opposite problem:

1. Given α, β, γ, find $\overline{i'_L}$, $\overline{j'_L}$, $\overline{k'_L}$
2. Given $\overline{i'_L}$, $\overline{j'_L}$, $\overline{k'_L}$ find α, β, γ.

The solution to the first problem is

$\overline{i'_L}$ = $(\cos\alpha\cos\gamma - \sin\alpha\cos\beta\sin\gamma)\,\hat{\imath} + (\sin\alpha\cos\gamma + \cos\alpha\cos\beta\sin\gamma)\,\hat{\jmath} + \sin\beta\sin\gamma\,\hat{k}$

$\overline{j'_L}$ = $-(\cos\alpha\sin\gamma + \sin\alpha\cos\beta\cos\gamma)\,\hat{\imath} - (\sin\alpha\sin\gamma - \cos\alpha\cos\beta\cos\gamma)\,\hat{\jmath} + \sin\beta\cos\gamma\,\hat{k}$

$\overline{k_i}$ = $\sin\alpha\sin\beta\,\hat{\imath} - \cos\alpha\sin\beta\,\hat{\jmath} + \cos\beta\,\hat{k}$

The second problem is a little harder:

Given l_{ij} such that

$$\overline{i'_L} = l_{11}\,\bar{i} + l_{12}\,\bar{j} + l_{13}\,\bar{k}$$
$$\overline{j'_L} = l_{21}\,\bar{i} + l_{22}\,\bar{j} + l_{13}\,\bar{k}$$
$$\overline{k'_L} = l_{31}\,\bar{i} + l_{32}\,\bar{j} + l_{33}\,\bar{k}$$

Find the corresponding α, β, γ.

From the above,

$$l_{11} = \cos\alpha \cos\gamma - \sin\alpha \cos\beta \sin\gamma \tag{1}$$

$$l_{12} = \sin\alpha \cos\gamma + \cos\alpha \cos\beta \sin\gamma \tag{2}$$

$$l_{13} = \sin\beta \sin\gamma \tag{3}$$

$$l_{21} = -(\cos\alpha \sin\gamma + \sin\alpha \cos\beta \cos\gamma) \tag{4}$$

$$l_{22} = -(\sin\alpha \sin\gamma - \cos\alpha \cos\beta \cos\gamma) \tag{5}$$

$$l_{23} = \sin\beta \cos\gamma \tag{6}$$

$$l_{31} = \sin\alpha \sin\beta \tag{7}$$

$$l_{32} = -\cos\alpha \sin\beta \tag{8}$$

$$l_{33} = \cos\beta \tag{9}$$

From (9)

$$\beta = \arccos(l_{33}) \;;\quad 0 \le \beta \le \pi \tag{10}$$

Then if $\sin\beta \neq 0$ then from (7) and (8),

$$\sin\alpha = \frac{l_{31}}{\sin\beta} \tag{11}$$

$$\cos\alpha = -\frac{l_{32}}{\sin\beta} \tag{12}$$

From (11) and (12), we get α, where $0 \le \alpha \le 2\pi$

From (3) and (9)

$$\sin\gamma = \frac{l_{13}}{\sin\beta} \tag{13}$$

$$\cos\gamma = \frac{l_{23}}{\sin\beta} \tag{14}$$

From (13) and (14), we get γ, where $0 \le \gamma \le 2\pi$

On the other hand, if $\sin\beta = 0$, then set $\gamma = 0$, and from (1) and (2),

$$\cos\alpha = \frac{l_{11}}{\cos\gamma} \tag{15}$$

$$\sin\alpha = \frac{l_{12}}{\cos\gamma} \tag{16}$$

The result of the vector multiplication is

$$M = \begin{pmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{pmatrix} \quad \text{, where}$$

$m_{11} = \cos\alpha \cos\gamma - \sin\alpha \cos\beta \sin\gamma$

$m_{12} = -\cos\alpha \sin\gamma - \sin\alpha \cos\beta \cos\gamma$

$m_{13} = \sin\alpha \sin\beta$

$m_{21} = \sin\alpha \cos\gamma + \cos\alpha \cos\beta \sin\gamma$

$m_{22} = -\sin\alpha \sin\gamma + \cos\alpha \cos\beta \cos\gamma$

$m_{23} = -\cos\alpha \sin\beta$

$m_{31} = \sin\beta \sin\gamma$

$m_{32} = \sin\beta \cos\gamma$

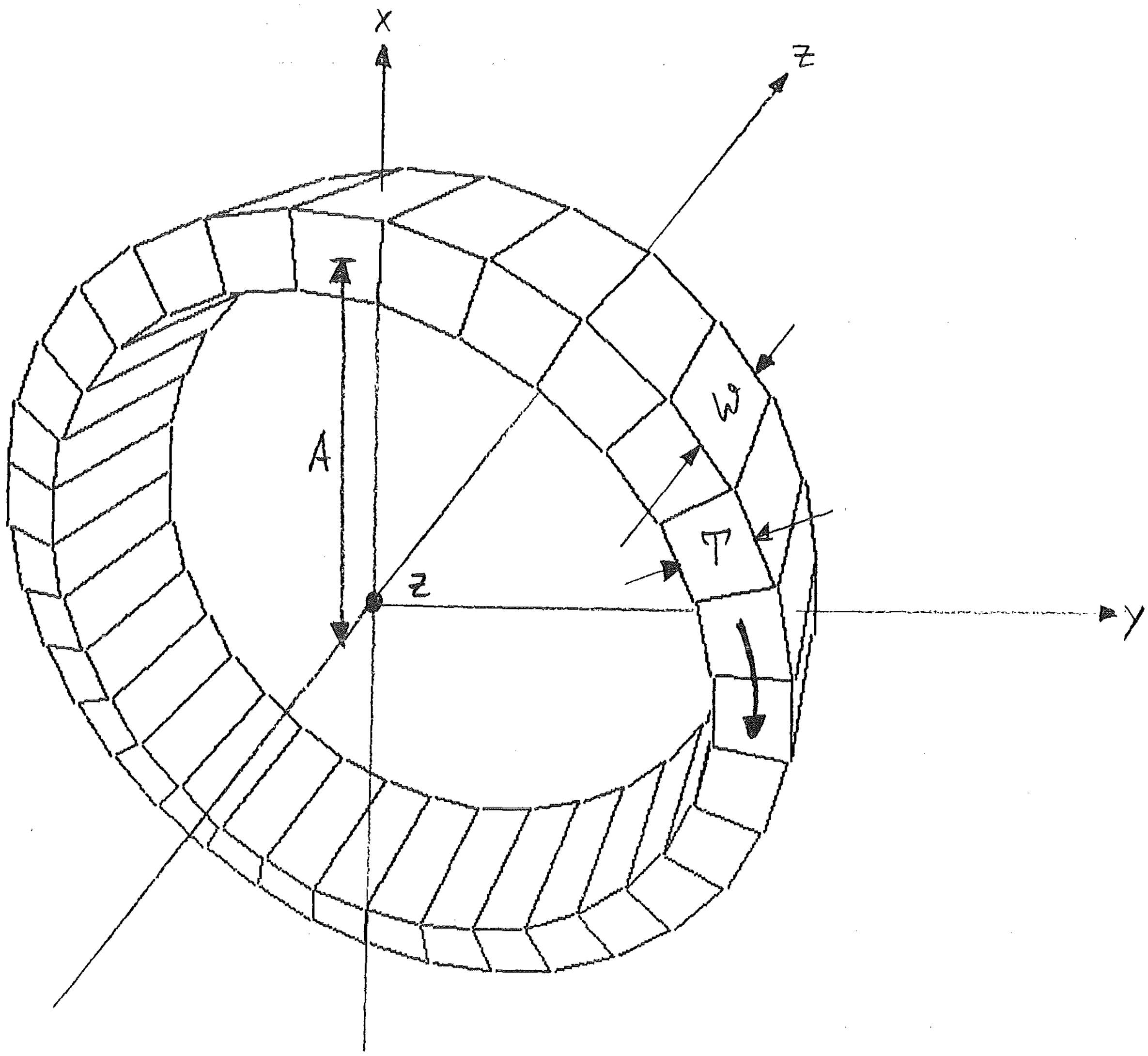
$m_{33} = \cos\beta$

So, the transformation matrix M is found.

4. Overview of the Families of Coils

4.1 SOLENOID(S)

Call: SOL Z, A, W, T, J $



Z = Distance of center of the solenoid to the origin, measured along the Z-axis

A = Radius to the center of the cross section

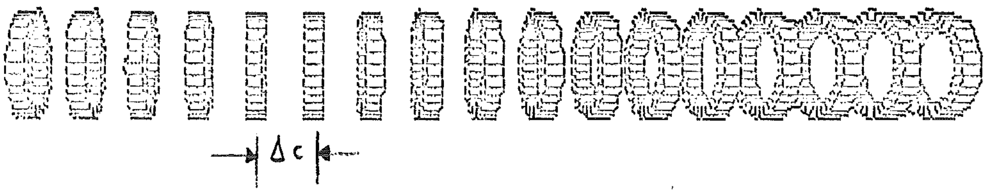
W = Axial length

T = Radial thickness

J = Current density (the current direction is shown by arrows). Reference cross section is W·T.

E Q U I D I S T A N T   S O L E N O I D S

Call: SOL Z, A, W, T, J, Δc, N. Ø



Z, A, W, T, J as for solenoids

Δc = distance between coil centers

N. = number of coils

Example of EIG - Karlsruhe

```
COIL = CCC
SOL
5
Ø.      21Ø.      7Ø.      6Ø.      218Ø.
COIL = BC17NBTI
SOL
7
-33Ø.      152.      16Ø.      36.      275Ø.      66Ø      2.
```

Number of input data:

5	for one solenoid
7	for equidistant solenoids an Z-axis
8	for one displaced solenoid
11	for one rotated solenoid
14	for one displaced and rotated solenoid

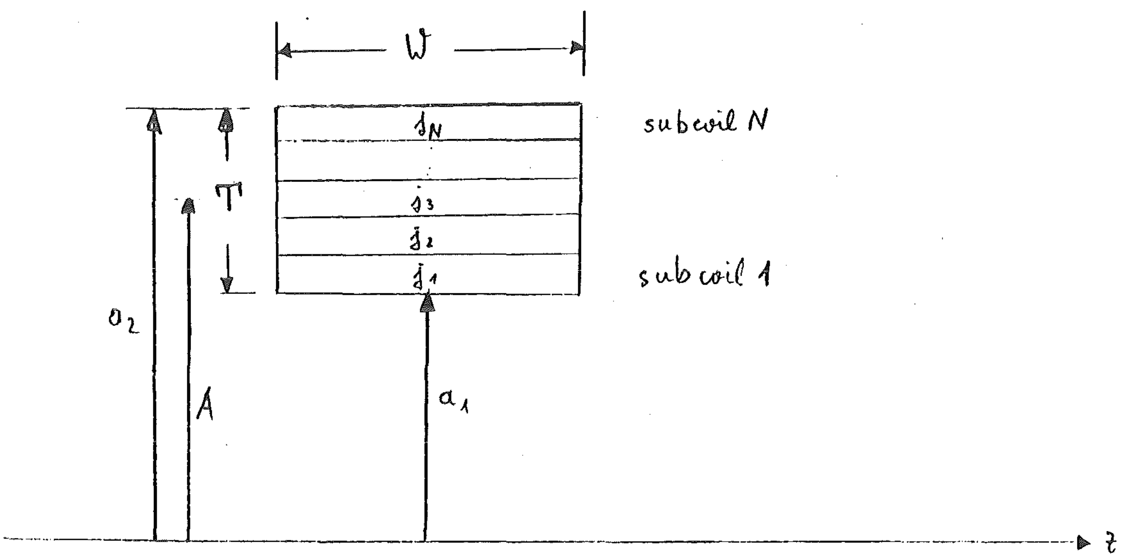
B I T T E R   C O I L

see D.B. Montgomery: Solenoid Magnet Design, Wiley-Interscience 1969, p. 23 ff.

The current density in a Bitter coil varies with radius as

$$j = j(r) = j_1 \cdot \frac{a_1}{r}$$

The coil is subdivided in N subcoils to approximate the 1/r current distribution as shown in the following figure.



It is

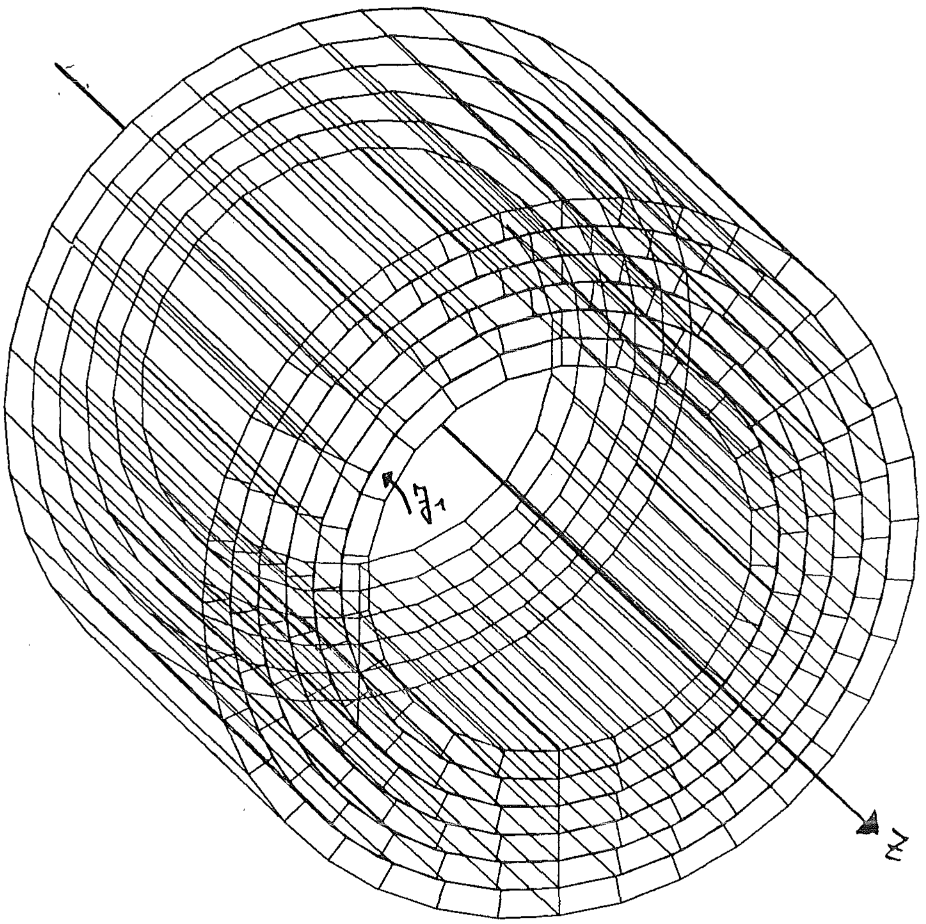
$$a_1 = A - T/2$$
$$a_2 = A + T/2$$
$$\alpha = a_2/a_1$$
$$\Delta t = T/N$$
$$\Delta r = \frac{a_2 - a_1}{N} = \frac{a_1(\alpha - 1)}{N} = \frac{a_1}{N'}$$
$$N' = \frac{N}{\alpha - 1}$$

For each subcoil is:

$$r_n = a_1 + (n - \tfrac{1}{2})\Delta r = a_1\left(1 + \left(\frac{n - 1/2}{N'}\right)\right) \qquad n = 1, 2, \ldots, N$$

$$\overline{J}_n = \overline{j_i \cdot \frac{a_1}{r_n}} = N' \, j_1 \ln \frac{N' + n}{N'+n-1}$$

Call: BIT Z, A, W, T, N., J_1 $



Z = Distance of center of the Bitter coil to the origin, measured along the Z-axis.

A = Radius to the center line of the cross section

W = Axial length

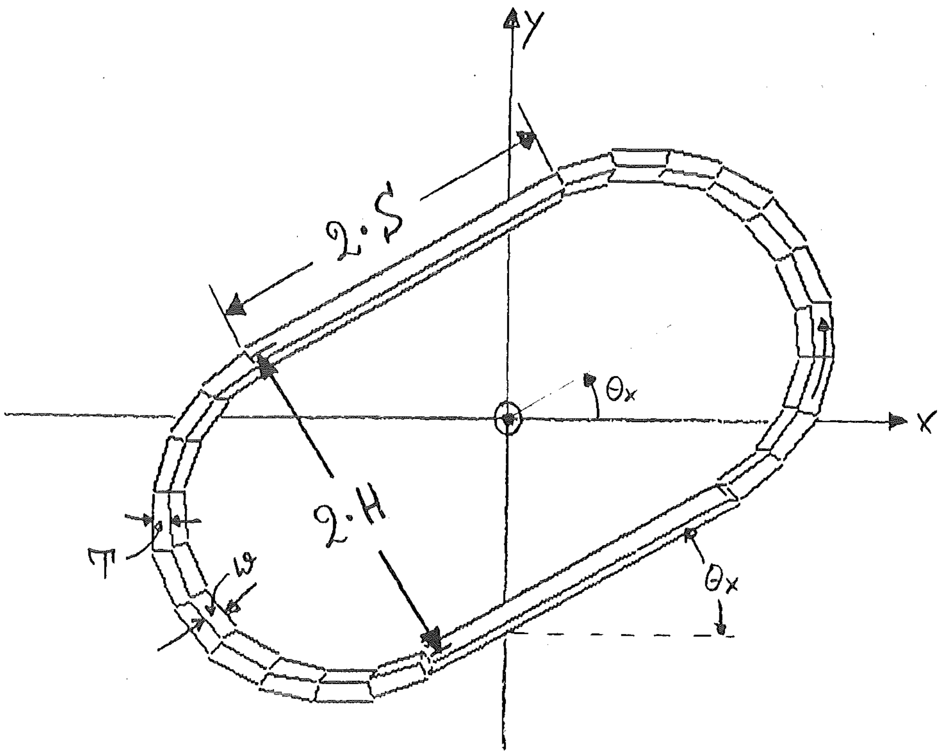
T = Radial thickness

N. = Number of radial subdivisions, to approximate 1/r current distribution. The decimal point is a must.

J_1 = Current density of the inner subdivision

4.2 RACE TRACK COIL

Call: RT Z, H, S, Θ_X, W, T, J $



Z	=	Distance from center of the figure to the origin measured along the Z-axis
H	=	half width
S	=	half length of straight section
Θ_X	=	Inclination of "long" axis measured from X-axis
W	=	axial width
T	=	radial width
J	=	Current density (direction shown by the arrow)

Note: 1. The plane of the RT is parallel to the x-y-plane

2. If S = 0, RT is the same as SOL

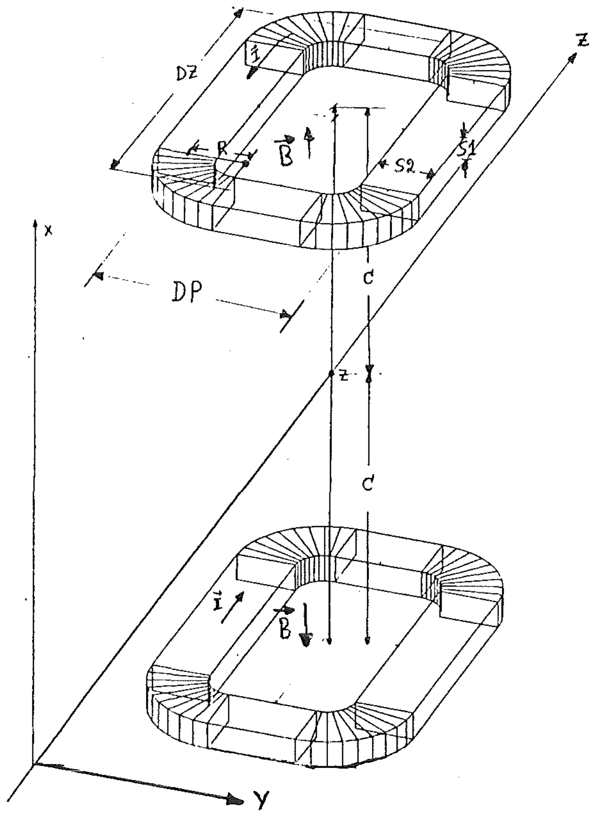
4.3 W I N D O W F R A M E C O I L (S)

Call: WFX Z, C, DZ, DP, R, S1, S2, J $

The WFX has two coils whose planes are parallel to the Y-Z plane. They have quarter-circle corners. They are at an equal distance from the Z-axis and have their current going in opposite directions, so the flux goes out of their center holes, away from the Z - axis. All the straight sections must have non-zero length. This requires that:

DZ > 2R

and DP > 2R



Z = Z-position of center of coil set

C = Distance in X-direction to the coil center of either WF

DZ = Total length in Z-direction, with reference to the center line

DP = Total length in Y-direction, with reference to the center line

R = Radius of circular corner, with reference to the center line

S1 = Cross section dimension in the direction of the normal to the WF

S2 = Cross section dimension in the direction of the plane of the WF

J = Current density (direction shown by arrows)

Call: WFY Z, C, DZ, DP, R, S1, S2, J $

The WFY has two coils whose planes are parallel to the X-Z plane. They have quarter-circle corners. They are at an equal distance from the Z-axis and have their current going in opposite directions, so the flux goes out of their center holes, away from the Z-axis.

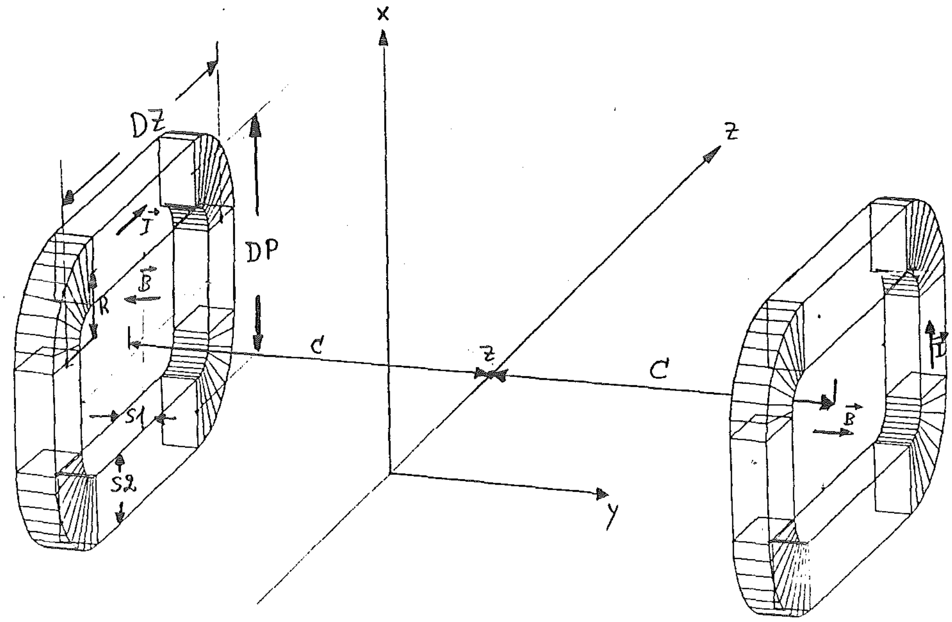
All of the straight sections must have non-zero length.

This requires that:

$$DZ > 2\ R$$

and

$$DP > 2\ R$$



Z	=	Z-position of center of coil set
C	=	Distance in Y-direction to the center of either WF
DZ	=	Total length in Z-direction with reference to the center line
DP	=	Total length in X-direction with reference to the center line
R	=	Radius of circular corner
S1	=	Cross section dimension in the direction of the normal to the WF
S2	=	Cross section dimension in the direction of the plane to the WF
J	=	Current density (direction shown by arrows)

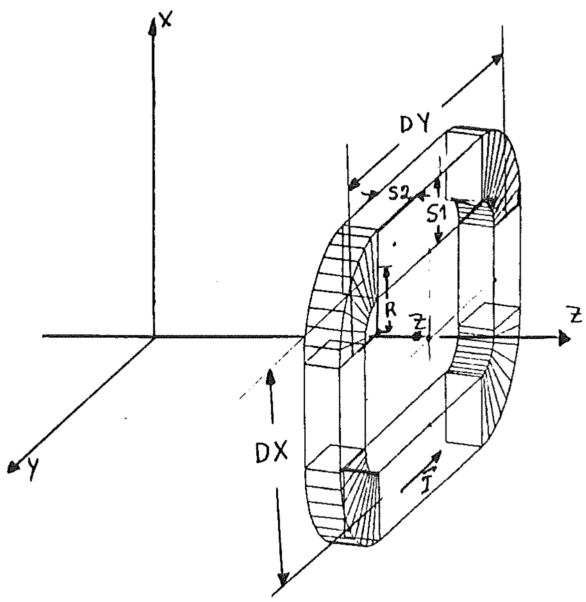
Call: WFZ Z, DX, DY, R, S1, S2, J $\not{S}$

The WFZ gives a Race-Track coil consisting of four GCE's and four arcs. The plane of the center line of the WFZ is parallel to the X-Y plane (or perpendicular to the Z-axis). All of the straight sections must have non-zero length. This requires that:

$$DY > 2R$$

and

$$DX > 2R$$



Z = Z-position of center line plane of the coil
DX = Total length of the center line in X-direction
DY = Total length of the center line in Y-direction
R = Center line radius of corners
S1 = Cross section dimension in the direction in the plane of WF
S2 = Cross section dimension in the Z-direction.
J = Current density (direction shown by arrows)

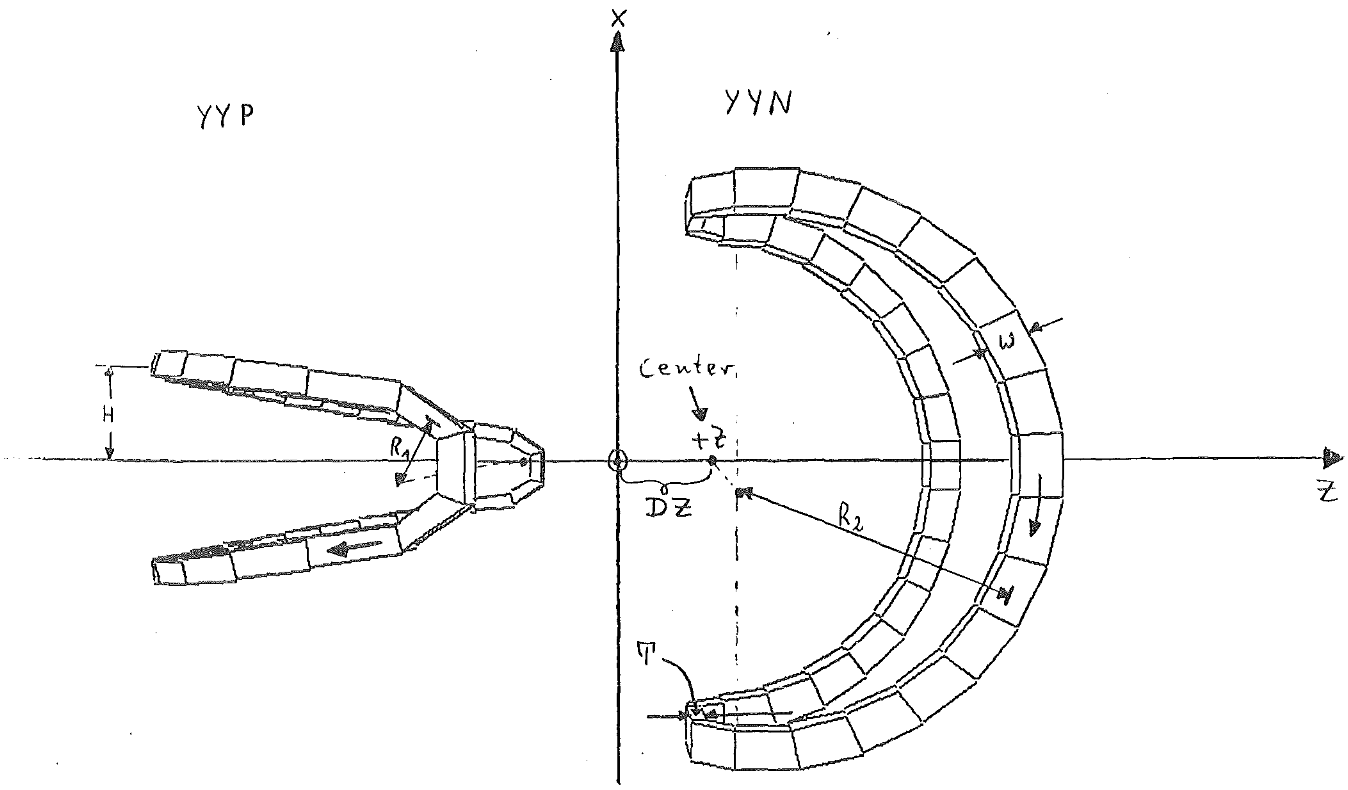
4.4 Y I N - Y A N G - C O I L (S)

Call:

YY R_2, R_1, H, DZ, W, T, J \$
YYN R_2, R_1, H, DZ, W, T, J \$
YYP R_2, R_1, H, DZ, W, T, J \$

YY gives a Yin-Yang pair, consisting of YYN and YYP;
The second and third calls give single coils.

A single coil consists of four arcs. Two of the four arcs are in planes parallel to the Y-Z-plane (YYN), resp. to the X-Z-plane (YYP). The other both arcs are generally in the direction of the conductor axis. They are half circles.



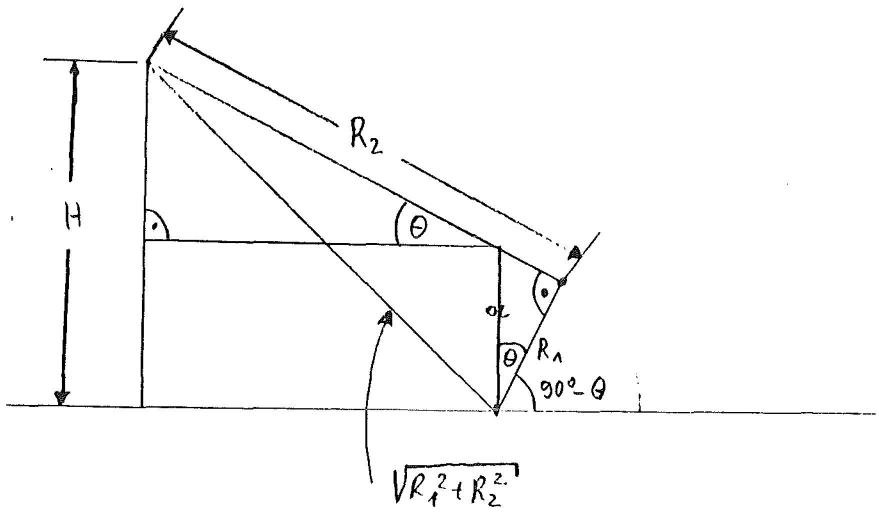
R_2 = Radius of big arc
R_1 = Radius of small arc
H = Half opening of big mouth
DZ = Distance of the coil center to the origin along the Z-axis
W = Width in R_2-direction
T = Width in R_1-direction
J = Current density (direction shown by arrows).

Notes:

1. If $H = R_1$, the two big arcs are parallel
2. For $\Delta z > 0$, the center of YYP is at $+ |\Delta z|$, but the center of YYN is at $- |\Delta z|$.
3. A geometric restriction on the input variables is

$$H < \sqrt{R_1^2 + R_2^2}$$

as shown in the following figures (projection of the YYN into the Y-Z plane):



For the angle Θ we get

$$\tan \Theta = \frac{HR_2 - R_1\sqrt{R_1^2+R_2^2-H^2}}{HR_1+R_2\sqrt{R_1^2+R_2^2-H^2}}$$

$$\text{or} \quad H^2 = \frac{R_1^2+R_2^2}{1+\left(\frac{R_1\tan\Theta-R_2}{R_2\tan\Theta+R_1}\right)}$$

To derive the relation above use the relations:

$$a = R_1/\cos\Theta; \quad \tan\Theta = (H-a)/\sqrt{R_1^2+R_2^2-H^2}; \quad \sin\Theta = \sqrt{1-\cos^2\Theta}$$

4.5 ELONGATED YIN-YANG COIL(S)

Call:

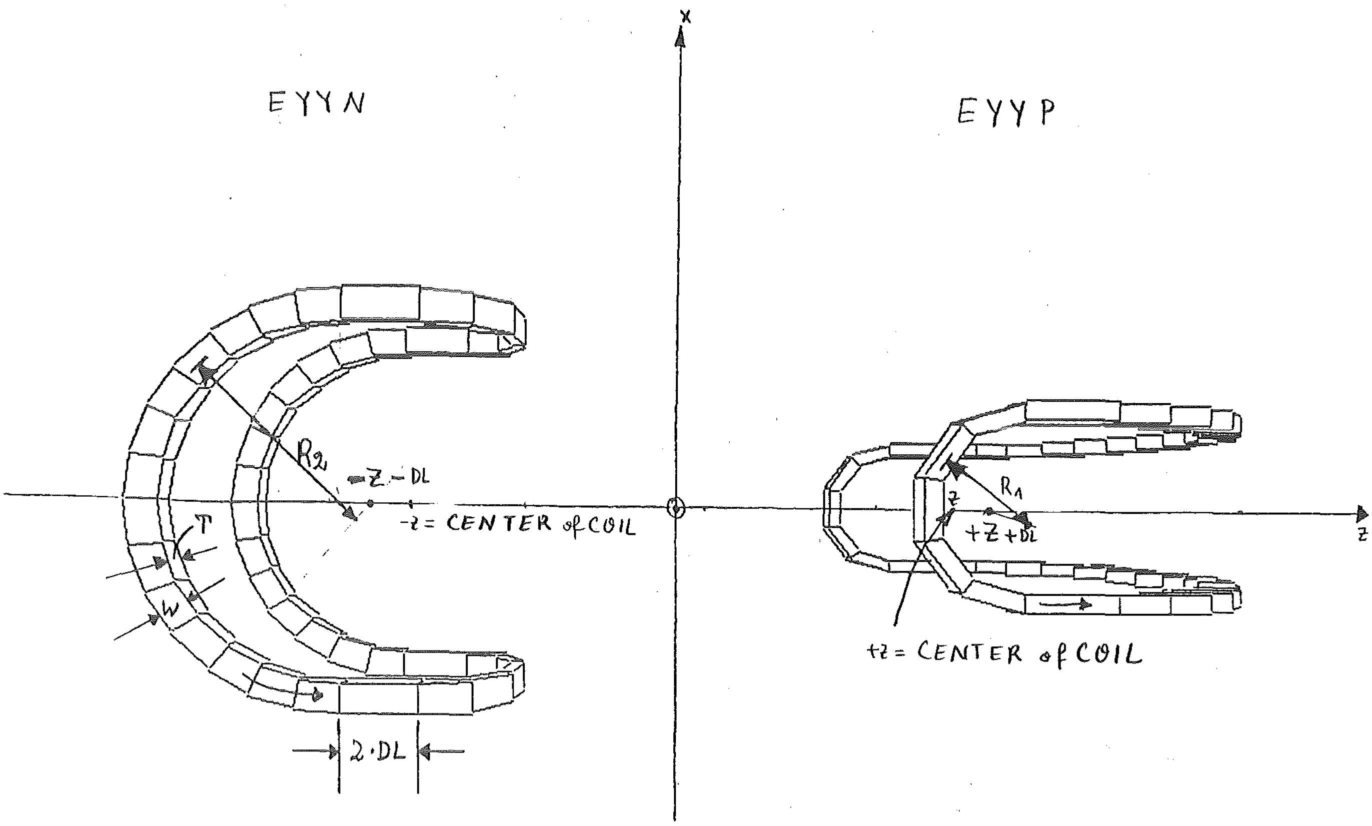
EYY R_2, R_1, DL, DZ, W, T, J $

EYYN R_2, R_1, DL, DZ, W, T, J $

EYYP R_2, R_1, DL, DZ, W, T, J $

EYYZ R_2, R_1, DL, DZ, W, T, J $

EYY gives a elongated Yin-Yang-pair, consisting of EYYN and EYYP. The second and third calls give single coils. A single coil consists of four arcs and (if DL $\neq$ 0) four straight sections. All the arcs are half-circles (i.e. $H = R_1$).



R_2 = Radius of big arc

R_1 = Radius of small arc

DL = Half-Length of added straight section

DZ = Distance from center of gravity of the added straight section to the origin, measured along the Z-axis.

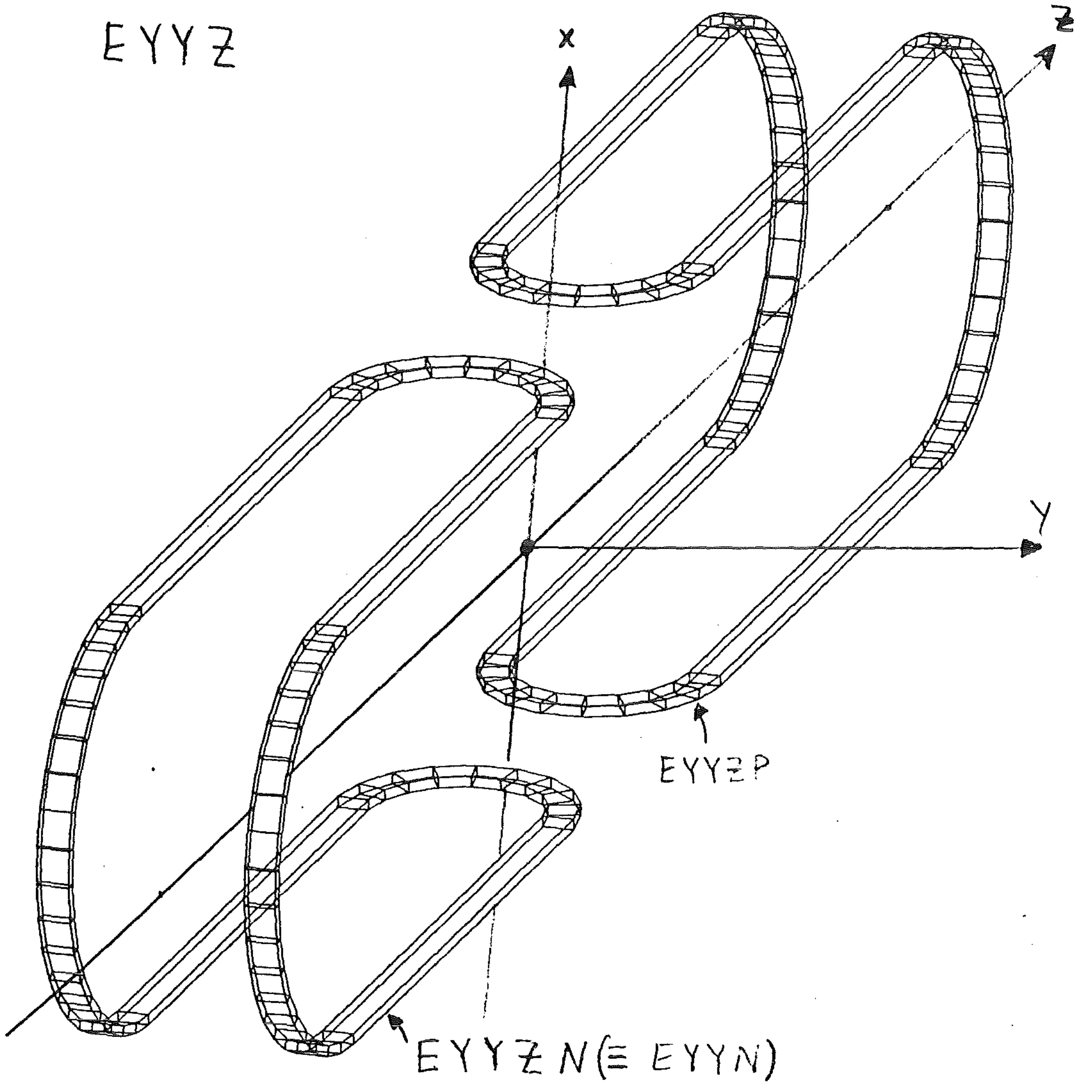
W = Width in R_2-direction

T = Width in R_1-direction

J = Current density (direction shown by arrows)

Notes: 1. If in YY $H = R_1$ and in EYY DL = 0, then the same coil is generated.

2. A rotation of 90^0 of the EYYP about the Z-axis gives EYYZ from EYY.



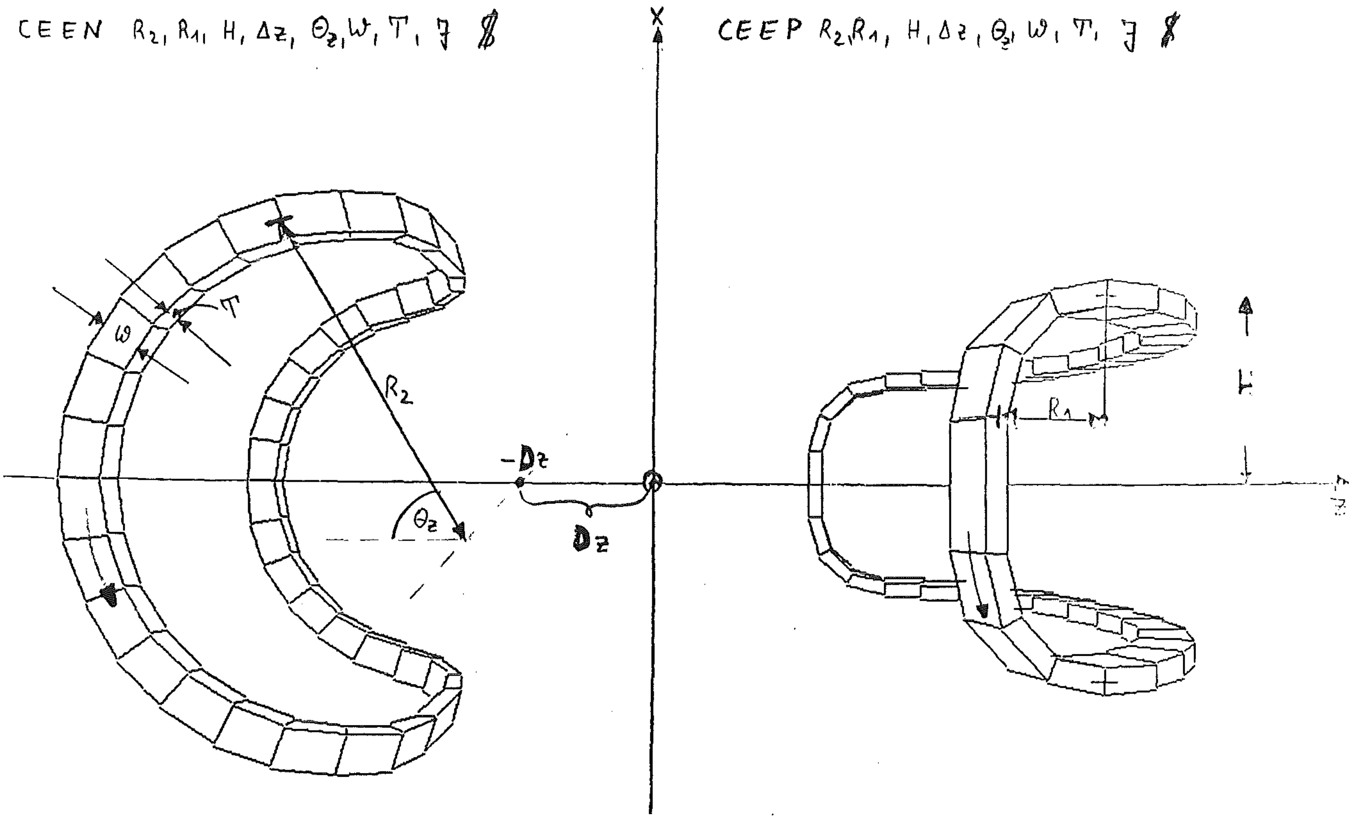
4.6 C-SHAPED COIL(S)

Call:

CEE R_2, R_1, H, DZ, Θ_Z, W, T, J \$
CEEN R_2, R_1, H, DZ, Θ_Z, W, T, J \$
CEEP R_2, R_1, H, DZ, Θ_Z, W, T, J \$
CEEZ R_2, R_1, H, DZ, Θ_Z, W, T, J \$

CEE gives a C-shaped coil pair CEEN and CEEP. The second and third calls give single coils.

A single coil consists of six arcs and 2 straight sections, in general. Two arcs have the radius R_2 and four arcs have the radius R_1. H is the half average distance between the both big arcs with the radius R_2. $H \geq R_1$ is required; no straight section exists for $H = R_1$.



R_2 = Radius of big arc
R_1 = Radius of small arc
H = Half opening distance of big mouth
DZ = Distance from the axis of the big arcs (center of the coil) to the origin measured along the Z-axis.

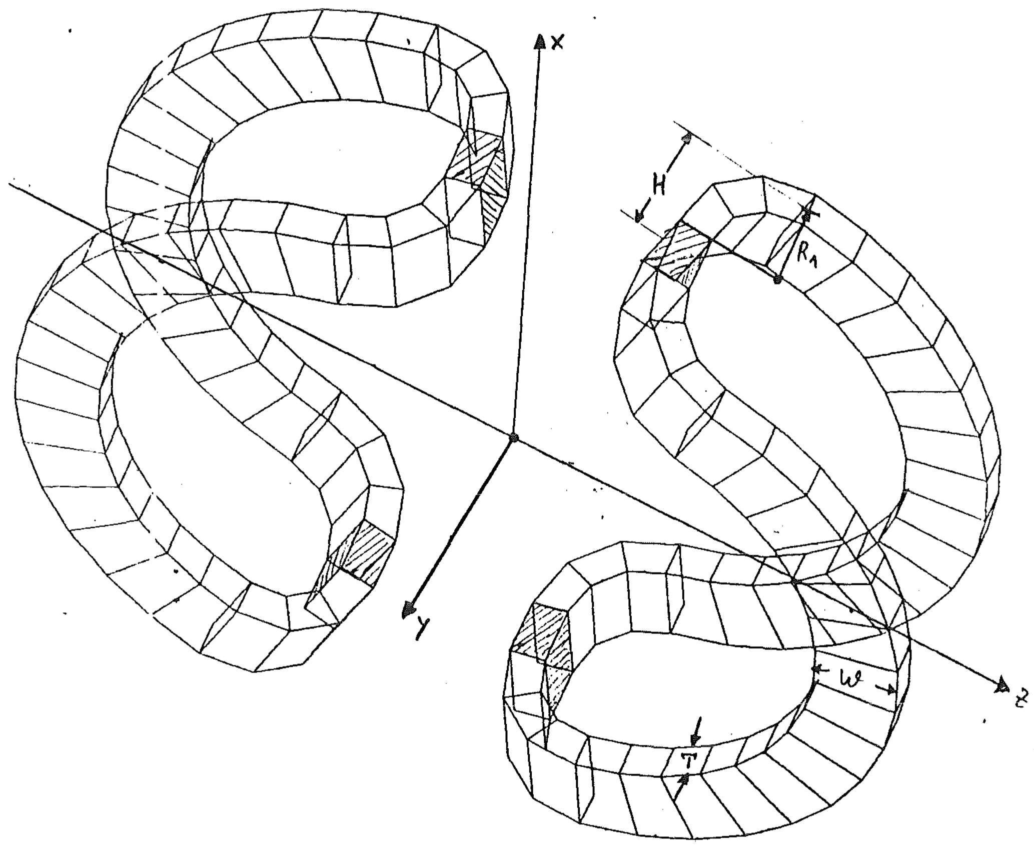
Θ_z = Half of the angle subtended by the big arc
W = Width of the coil in R_2-direction
T = Width of the coil in R_1-direction
J = Current density (direction shown by arrows)

Note: 1. The CEE, consisting of the CEEN and the CEEP, has its center at the origin. Suppose there were another parameter Z in the calling sequence for CEE, which shifted the figure, so that Z was the center. This can be accomplished as follows:

CEEN R_2, R_1, H, - (Z - DZ), Θ_z, W, T, J $

CEEP R_2, R_1, H, (Z + DZ), Θ_z, W, T, J $

2. The CEEZ is got from the CEE by a 90^0 rotation of the positive half around the Z-axis. In all other respects, the CEEZ is the same as the CEE.



3. Versions of EIG after 4 /16/80 have the rotation and translational capabilities. Therefore, this CEEZ can now be got from the CEEN and CEEP, as follows:

   CEEZ R_2, R_1, H, DZ, Θ_z, W, T, J \$

   is the same as

   CEEN R_2, R_1, H, DZ, Θ_z, W, T, J \$
   CEEP R_2, R_1, H, DZ, Θ_z, W, T, J
   0. 0. 0. 90. 0. 0. \$

4. We get from CEEN a CEEP-coil by the following procedure

   a) Rotation by 180^0 around the X-axis
   b) Rotation by 90^0 around the Z-axis
   c) Inversion of current direction

5. For $\Delta z > 0$, a CEEP is located at + $|\Delta z|$, and a CEEN is located at - $|\Delta z|$.

4.7 REVERSED C-SHAPED COIL(S)

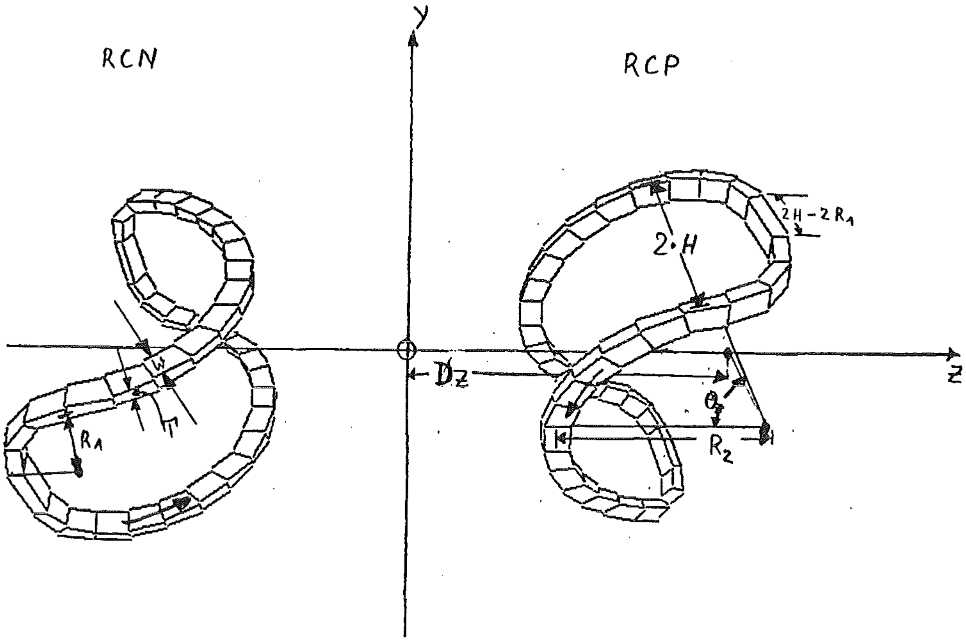
Call:

$RC \quad R_2, R_1, H, DZ, \Theta_z, W, T, J \ \$$
$RCP \quad R_2, R_1, H, DZ, \Theta_z, W, T, J \ \$$
$RCN \quad R_2, R_1, H, DZ, \Theta_z, W, T, J \ \$$
$RCZ \quad R_2, R_1, H, DZ, \Theta_z, W, T, J \ \$$

RC gives a C-shaped reversed coil pair RCP and RCN. The second and third calls give single coils.

The RC is got from the CEE by rotating CEEP about an axis parallel to the Y-axis through the center of curvation of the big arcs and a similar rotation of CEEN about an axis parallel to the X-axis. Having done these rotations, the current directions are reversed and the CEEP is moved a distance 2 DZ toward the negative Z direction and the CEEN is translated a distance 2 DZ in the positive Z direction.

$RCN \quad R_2, R_1, H, DZ, \Theta_z, W, T, J \ \$$ $\qquad$ $RCP \quad R_2, R_1, H, DZ, \Theta_z, W, T, J \ \$$



R_2 = Radius of big arc
R_1 = Radius of small arc
H = Half opening distance of big mouth
DZ = Distance from the axis of the big arcs (center of the coil) to the origin, measured along the Z-axis
Θ_z = Half of the angle subtended by the big arc

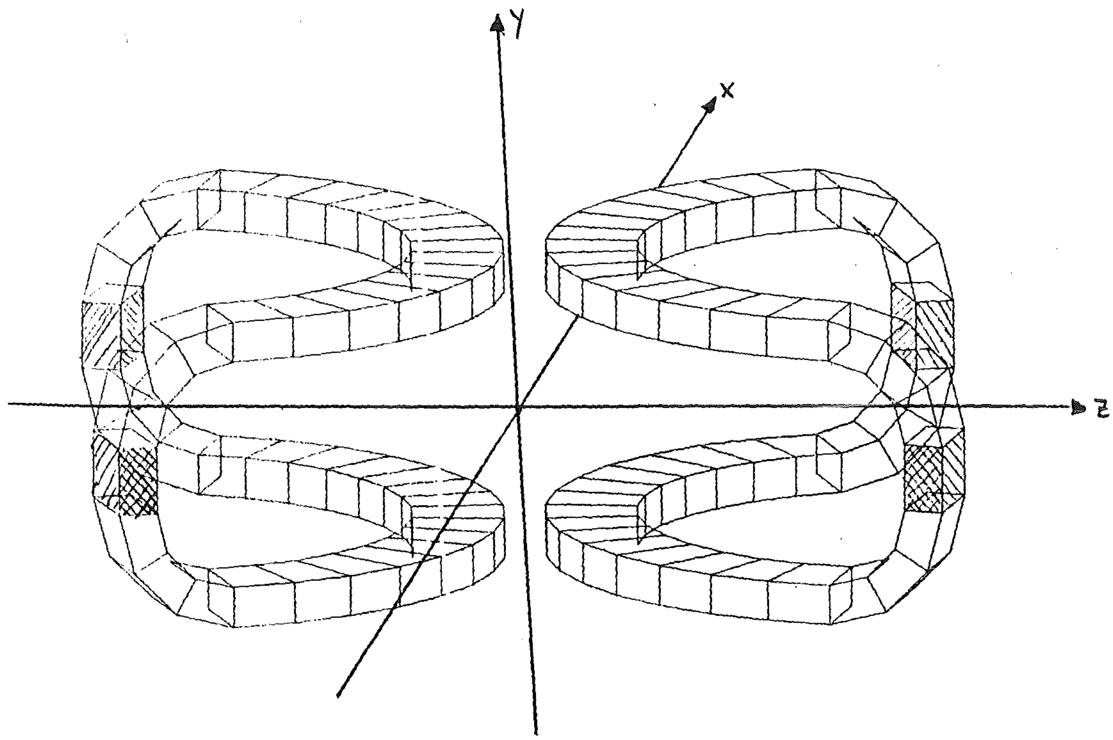
W = Width of the coil in R_2-direction

T = Width of the coil in R_1-direction

J = Current density (direction is shown by arrows)

Note: 1. If $H = R_1$, then the RC consists of arcs only. If $H > R_1$, then two GCE's in each coil RCN and RCP are added.

2. RCZ is got from RC by rotating the positive part of RC by 90^o around the Z-axis. In all other respects, the RCZ is the same as the RC.

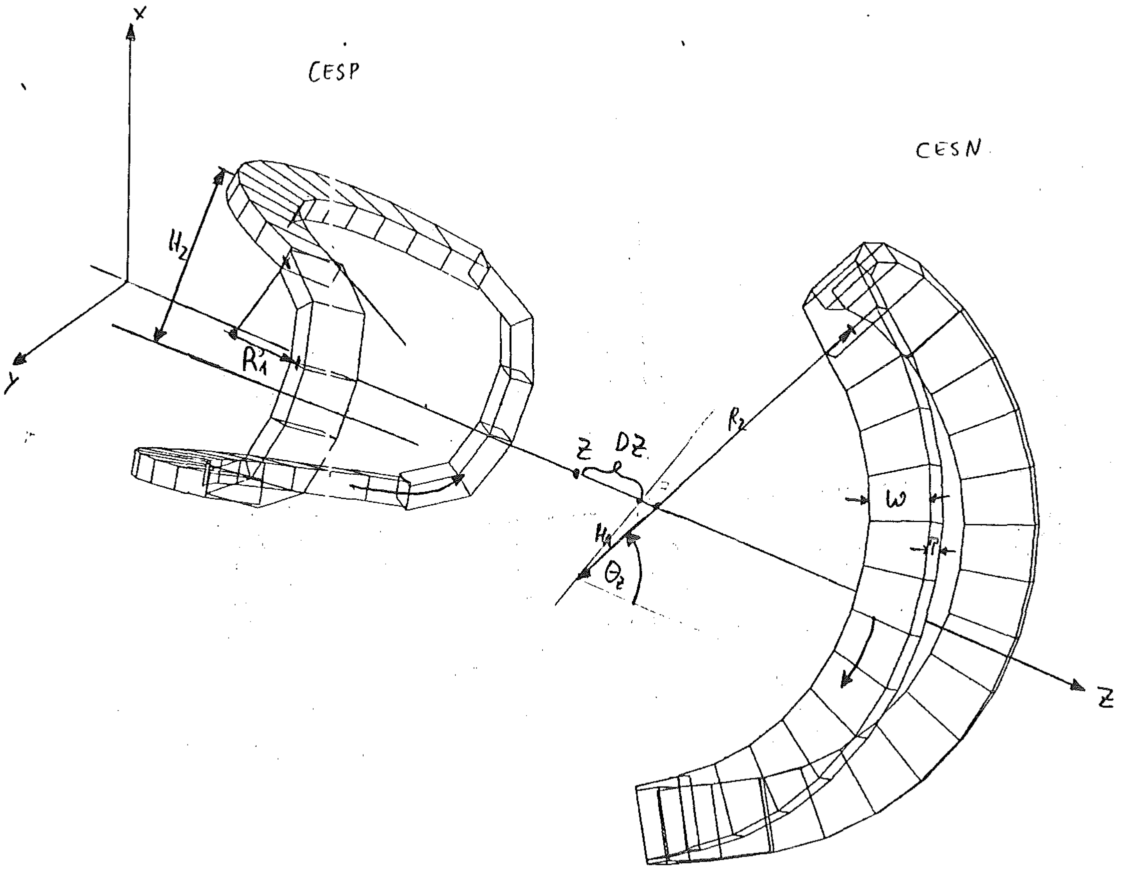


4.8 S Q U E E Z A B L E C - S H A P E D C O I L (S)

Call:

CES $Z, DZ, R_1, R_2, H_1, H_2, \Theta_z, W, T, J$ ∅
CESP $Z, DZ, R_1, R_2, H_1, H_2, \Theta_z, W, T, J$ ∅
CESN $Z, DZ, R_1, R_2, H_1, H_2, \Theta_z, W, T, J$ ∅

The squeezable C-shaped coils are related to the Yin-Yang coils.



Z = Z-position of the center of the coil (set).

DZ = Distance from the axis of the big arcs (coil center) to the point Z on the Z-axis

R_1 = Radius of the small arc

R_2 = Radius of the big arc

H_1 = Half throat opening of big arcs, measured along the axis of the big arcs

H_2 = Half mouth opening of big arc

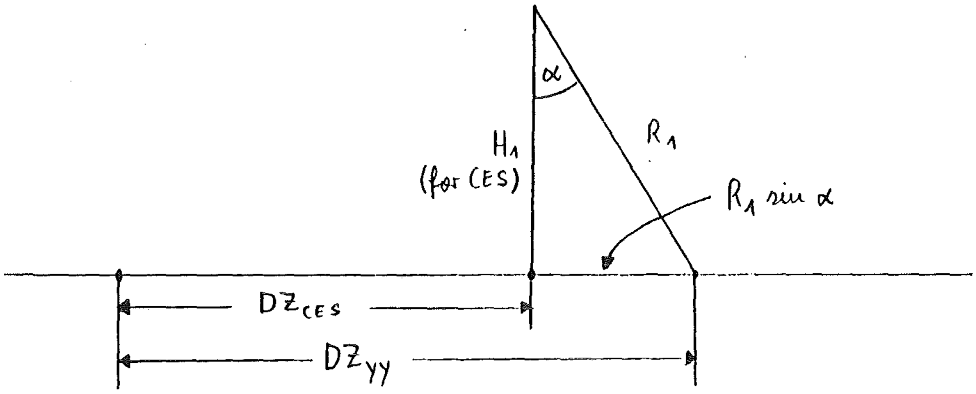
Θ_z = Half of the angle subtended by the big arc

W = Width in R_2-direction

T = Width in R_1-direction

J = Current density (direction shown by arrows).

The relation between CES and YY is the following:
Having picked up R_1, R_2 and H for YY, then the angle α, shown in the figure, can be calculated.



The angle α is given by

$$\alpha = \text{arc tan} \left(\frac{HR_2 - R_1\sqrt{S}}{HR_1 + R_2\sqrt{S}}\right)$$

where $$S = R_1^2 + R_2^2 - H^2.$$

A geometrical restriction is:

$$-1 \leq \frac{H_2 - H_1}{R_2} \leq 1$$

R_1 and R_2 remain for CES the same (as in YY) and

$$H_{2\ CES} = H_{YY}$$

$$H_{1\ CES} = R_1 \cos \alpha$$

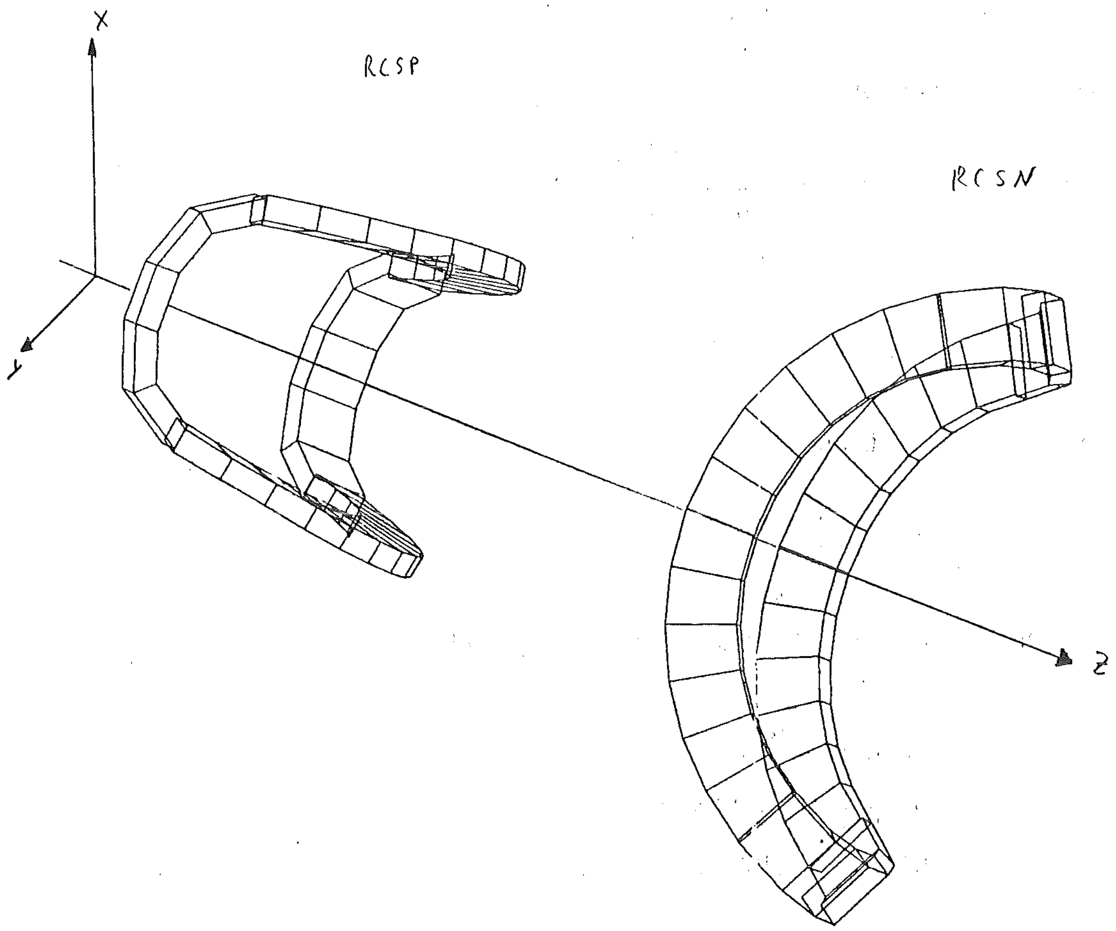
$$DZ_{CES} = (DZ)_{YY} - R_1 \sin \alpha$$

4.9 SQUEEZABLE REVERSED C-SHAPED COIL(S)

Call:

RCS Z, DZ, R_1, R_2, H_1, H_2, Θ_z, W, T, J \$
RCSP Z, DZ, R_1, R_2, H_1, H_2, Θ_z, W, T, J \$
RCSN Z, DZ, R_1, R_2, H_1, H_2, Θ_z, W, T, J \$

The RCS is got from the CES in the same way as the RC is got from the CEE. The numbering of the arcs is the same as for the RC.



The meaning of the parameters is the same as in CES.

4.10 C-SHAPED COIL(S) WITH EXTENDED BIG ARCS

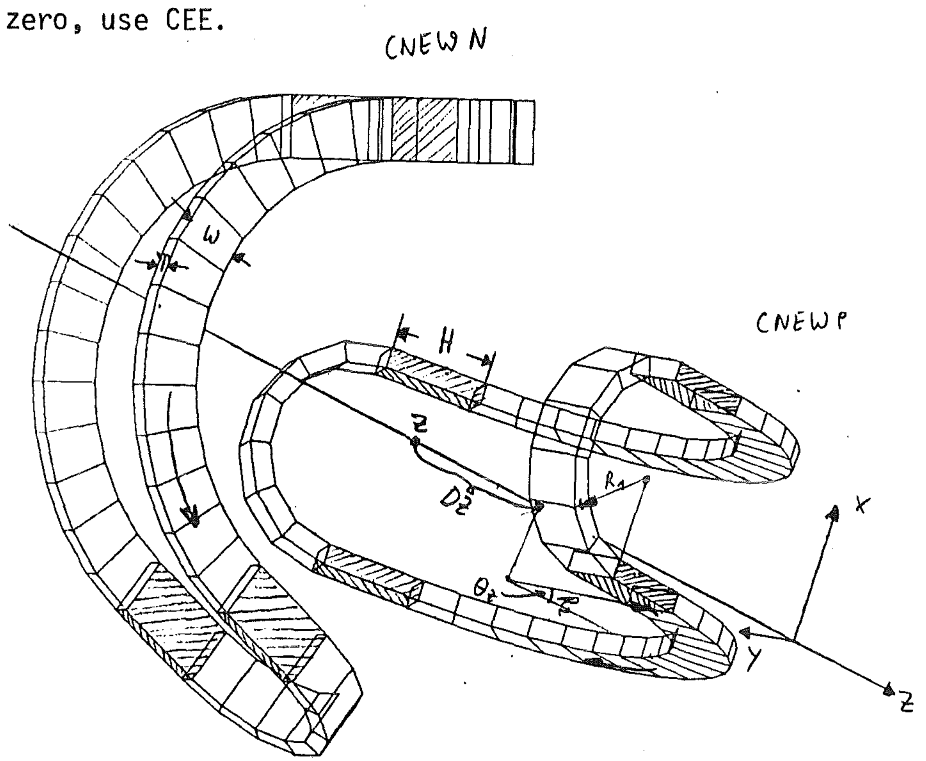
Call:

CNEW Z, DZ, H, R_2, R_1, Θ_z, W, T, J $

CNEWP Z, DZ, H, R_2, R_1, Θ_z, W, T, J $

CNEWN Z, DZ, H, R_2, R_1, Θ_z, W, T, J $

CNEW produces two coils, each consisting of 4 arcs and 4 GCE's. Therefore there are 8 arcs and 8 GCE's. The first 4 of each are for the CNEWP, and the last 4 one for the CNEWN. A restriction is H > 0. If H is zero, use CEE.



Z = Z-position of center of coil (set)

DZ = Distance from center of coil (set) to Z-position of the R_2 radius.

H = Total length of straight section. (H > 0)

R_2 = Radius of big arc

R_1 = Radius of small arc

Θ_z = Half of the angle subtended by the big arc.

W = Width in R_2-direction

T = Width in R_1-direction.

J = Current density (direction shown by arrows).

4.11 IOFFE-BAR TYPES

Call:

$\mathrm{IOFFE}\ \ \mathrm{IRI},\ Z,\ HL,\ \Theta_X,\ S_R,\ S_\Theta,\ J\ \$$

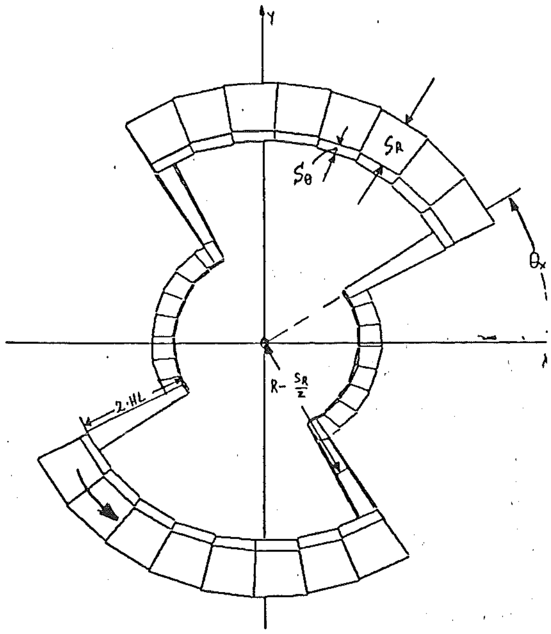
$\mathrm{IOFFE}\ -\mathrm{IRI},\ Z,\ HL,\ \Theta_X,\ S_R,\ S_\Theta,\ J\ \$$

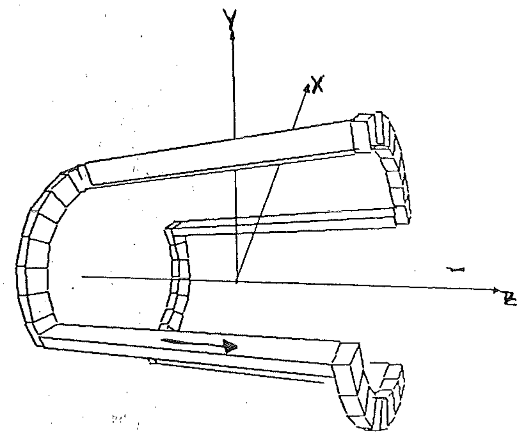
$\mathrm{IOFFR}\ \ R,\ Z,\ HL,\ \Theta_X,\ S_R,\ S_\Theta,\ RC,\ J\ \$$

$\mathrm{EIGHT}\ \ R,\ Z,\ HL,\ \Theta_X,\ S_R,\ S_\Theta,\ J\ \$$

There are two versions of the IOFFE. They are specified, as shown in the calls, by the sign of the radius R.

For R > 0, the IOFFE is as follows:





R = Radius of end arcs and also the distance from the Z-axis radially out to the center of the horizontal bars.

Z = Position on the Z-axis of the center of gravity of the figure

HL = Half length of horizontal bars

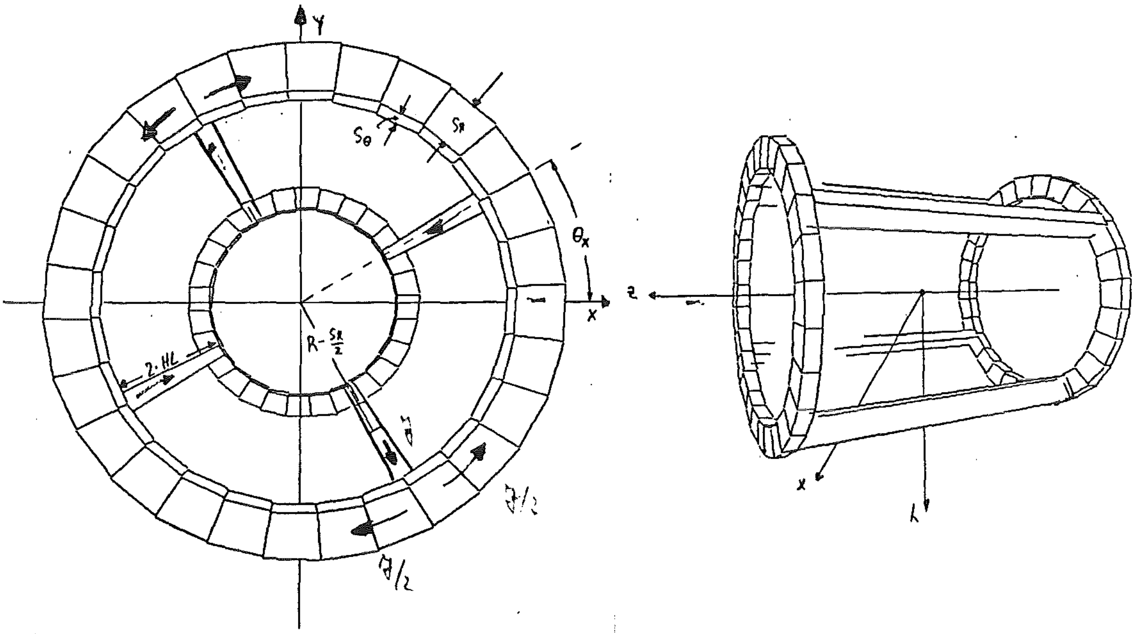
Θ_X = Angular position of the "top" bar (and of course all the other bars) from the X toward the Y-axis.

S_R = Width in radial direction

S_Θ = Width in axial or azimuthal direction

J = Current density (direction shown by arrows).

For R < 0, the ends are full circles. The current density in the straight section is J and J/2 in the end circles.

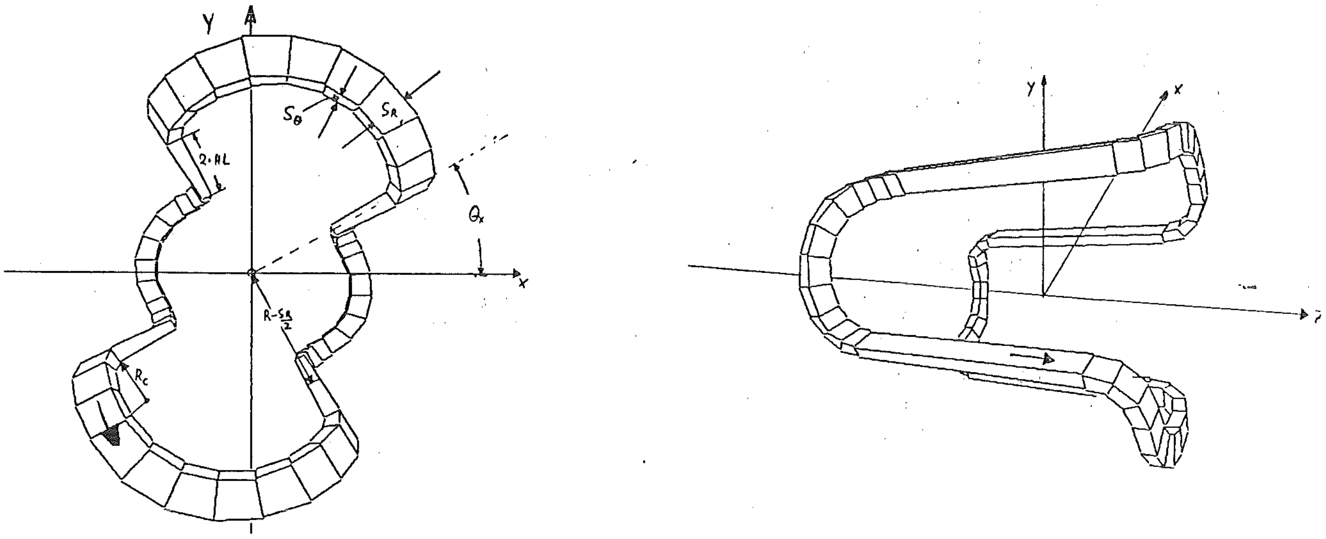


These IOFFE coils are only approximations of a real shape.

A much more realistic shape is produced by IOFFR. The call for IOFFR is

IOFFR R, Z, HL, Θ_X, S_R, S_Θ, RC, J $\not{\emptyset}$

IOFFR produces a coil shown in the figure below.



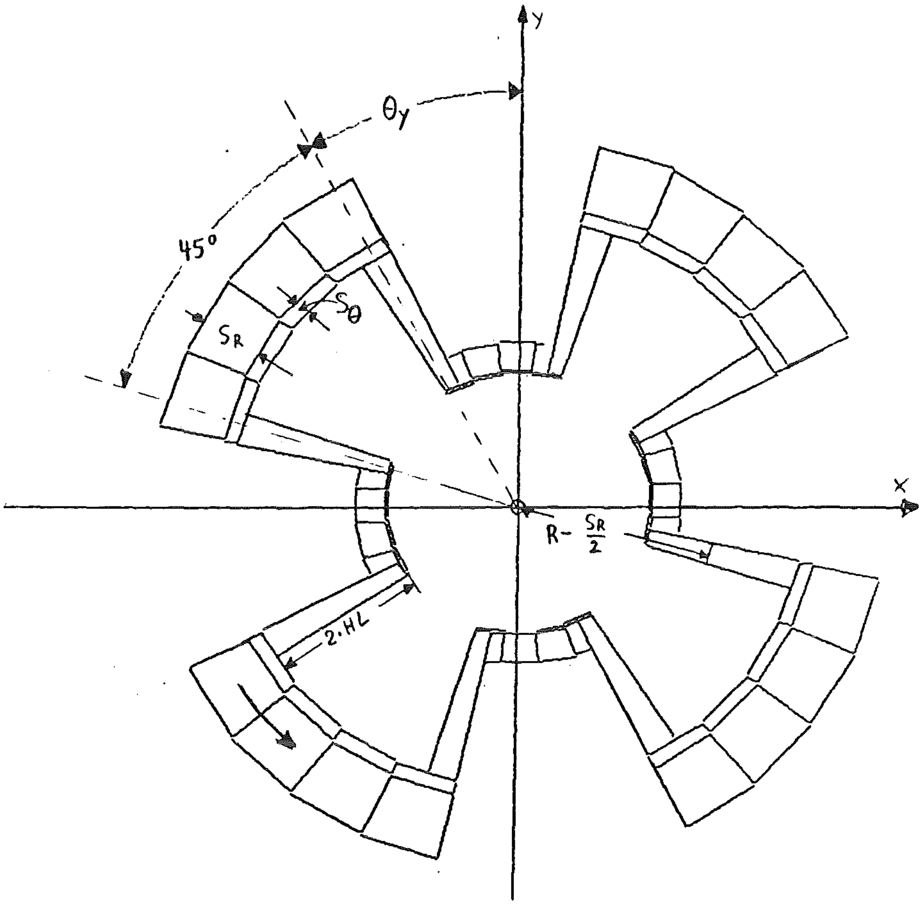
Note: R is not the radius of the end arcs

- R = Radial distance from the Z-axis to the center of the horizontal bars
- Z = Z-position of the center of gravity of the coil
- HL = Half length of center line in the Z-direction
- Θ_X = Angular position of the "top" bar from the X toward the Y-axis.
- S_R = Width in radial direction
- S_Θ = Width in axial or azimuthal direction
- RC = Inner radius of connecting arcs.
- J = Current density (direction shown by arrows)

The length of the straight sections is HL - (RC + S_Θ/2).
For RC > 0, the big arcs have a radius R - a, where a = RC + S_Θ/2.
For RC < 0, the big arcs have a radius R/cos β, where β = arctan (a/R).
IOFFR consists of 4 straight sections, 4 big arcs and 8 small connection arcs.

EIGHT produces 8 straight sections and 8 arcs for R > 0.

The call is EIGHT R, Z, HL, Θ_y, S_R, S_Θ, J $



R = Radius of end arcs and also the distance from the Z-axis radially out to the center of the horizontal bars.

Z = Z-position of the center of gravity of the figure

HL = Half length of horizontal bars

Θ_y = Θ_x = Angular position of the "top bar.

S_R = Width in radial direction

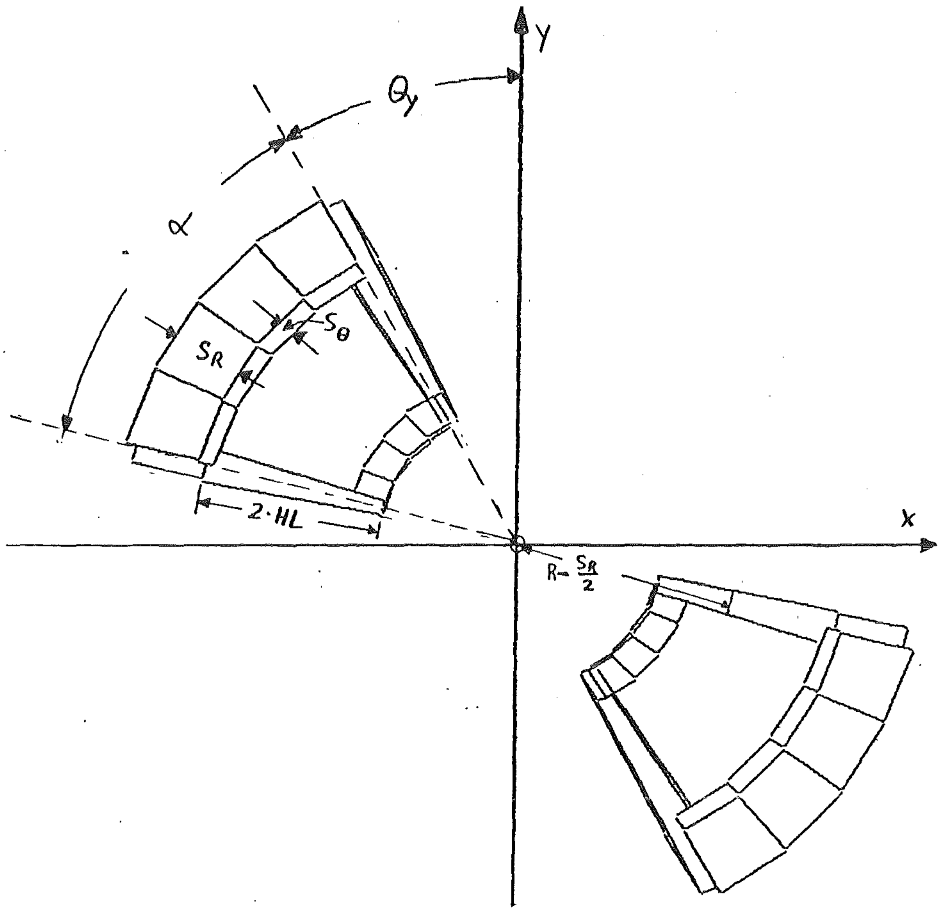
S_Θ = Width in axial or azimuthal direction

J = Current density (direction shown by arrows)

4.12 SADDLE COIL(S)

Call:

SADL R, Z, HL, Θ_y, α, S_R, S_Θ, J $



R = Radius of end arc and also the distance from the Z-axis radially out to the center of the horizontal bars

Z = Z-position of the center of gravity of the figure

HL = Half length of horizontal bars

Θ_y = Orientation to the Y-axis

α = Angular width of the coil

S_R = Width in radial direction

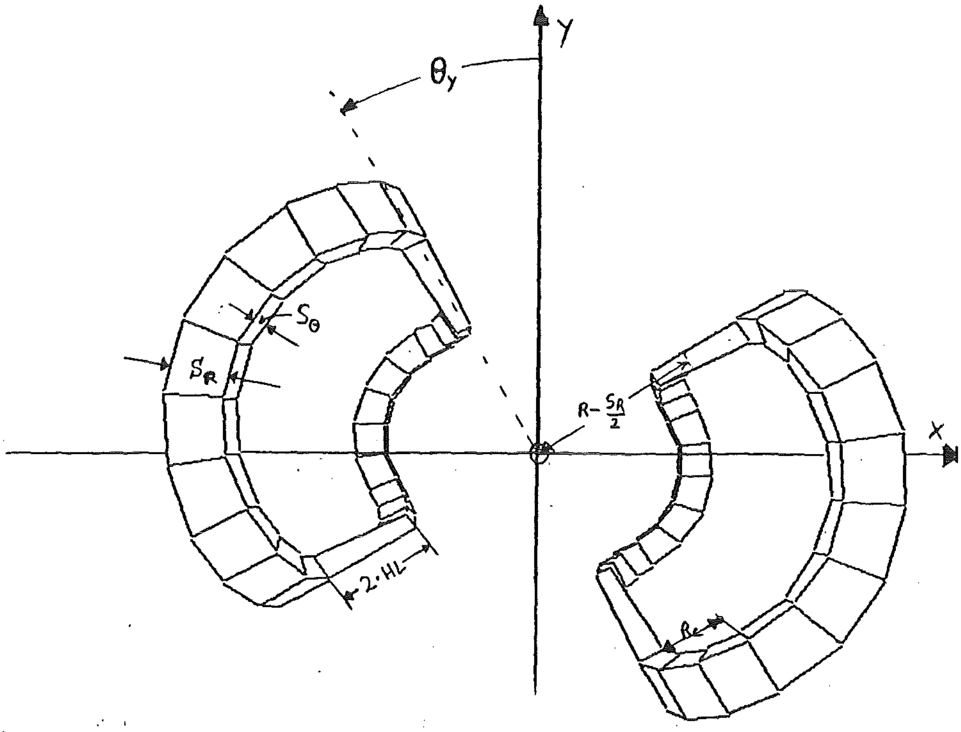
S_Θ = Width in axial or azimuthal direction

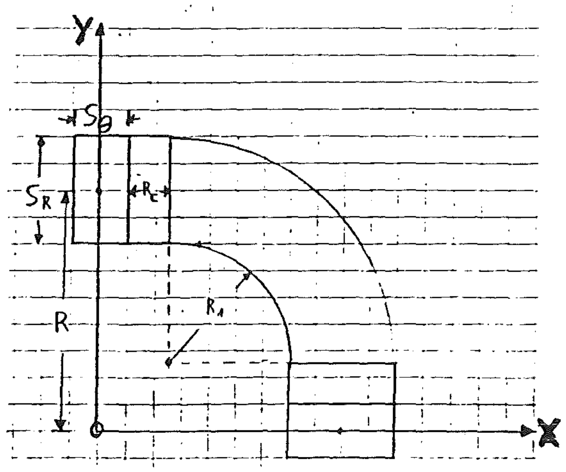
J = Angular width of the coil

A realistic saddle coil is produced by SADDLE.

Call:

SADDLE R, Z, HL, Θ_y, S_R, S_Θ, R_c, J $





R = Distance from the Z-axis radially out to the center of the horizontal bars

Z = Z-position of the center of gravity of the figure

HL = Half length of horizontal bars (compare IOFFR!)

Θ_y = Orientation to the Y-axis

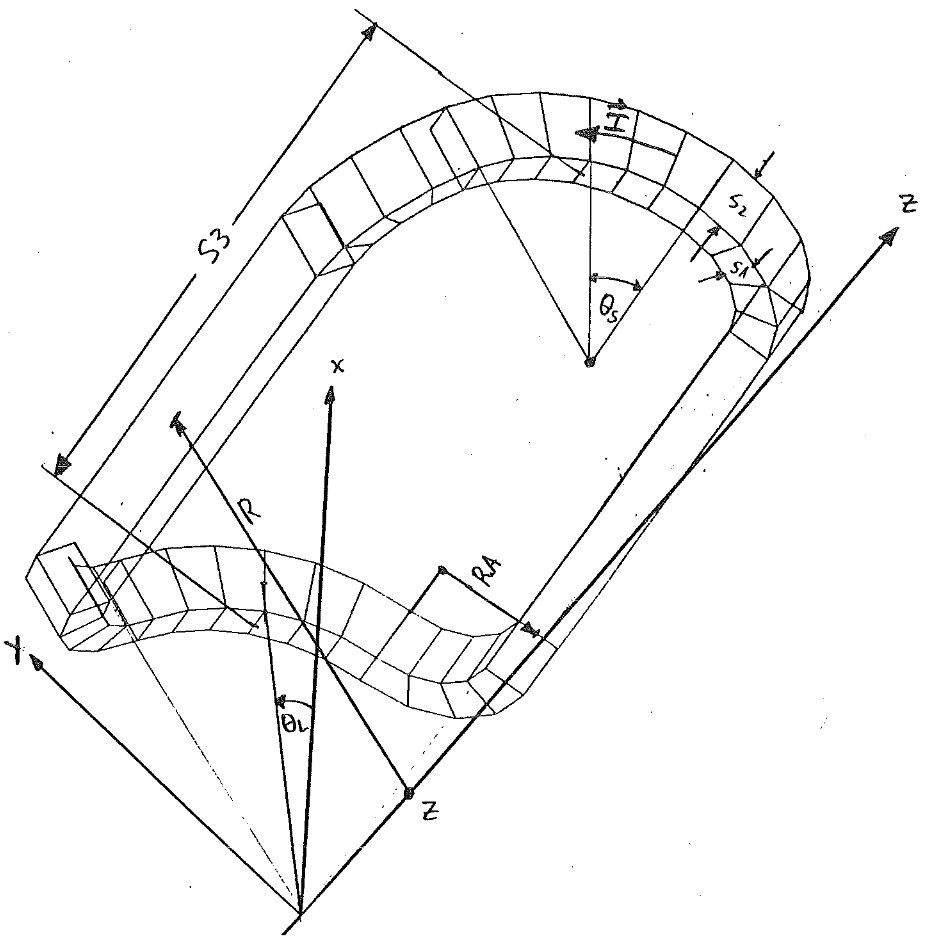
S_R = Width in radial direction

S_Θ = Width in axial or azimuthal direction

R_c = Radius of connection arcs

A single Saddle coil is produced by SAD.

Call: SAD Z, R, RA, Θ_L, Θ_S, S1, S2, S3, J ∅



Z = Z-position of coil center

R = Distance from Z-axis to the center line of the bars, measured in a plane perpendicular to the Z-axis.

RA = Radius of the four small corner arcs

Θ_L = Center-line angle, measured from X toward Y

Θ_S = Half angle subtended by end arcs

S1 = Axial cross section dimension of the two end arcs

S2 = Radial cross section dimension of the two end arcs

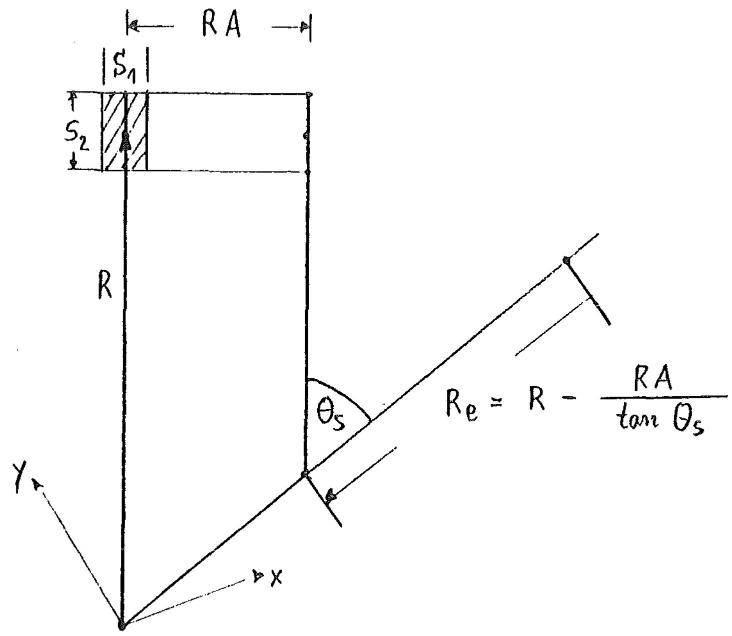
S3 = Z-diretion length referred to the center line.

J = Current density (direction shown by an arrow)

One should note, that the radius of the two end arcs is not R, but

$$R_e = R - \frac{RA}{\tan \Theta_S}$$

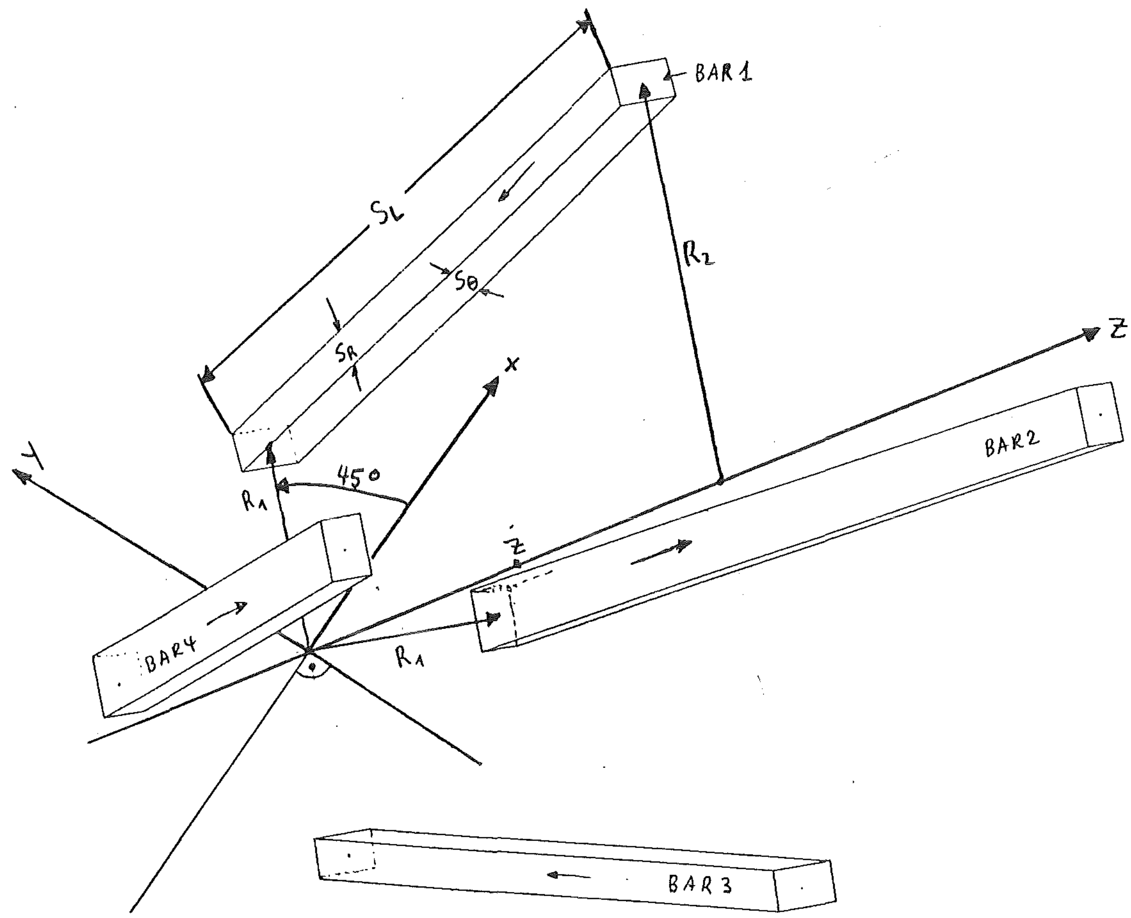
The SAD coil consits of two GCE's and six arcs. Two of these arcs are the big end arcs, and the remaining four arcs are the small corner arcs. These four arcs are defined with respect to the plane determined by the GCE cross section.



4.13 FOUR BARS

Call: CONE Z, R_1, R_2, S_R, S_Θ, S_L, J $

Note: CONE consists of four bars only. There are no circular arc ends



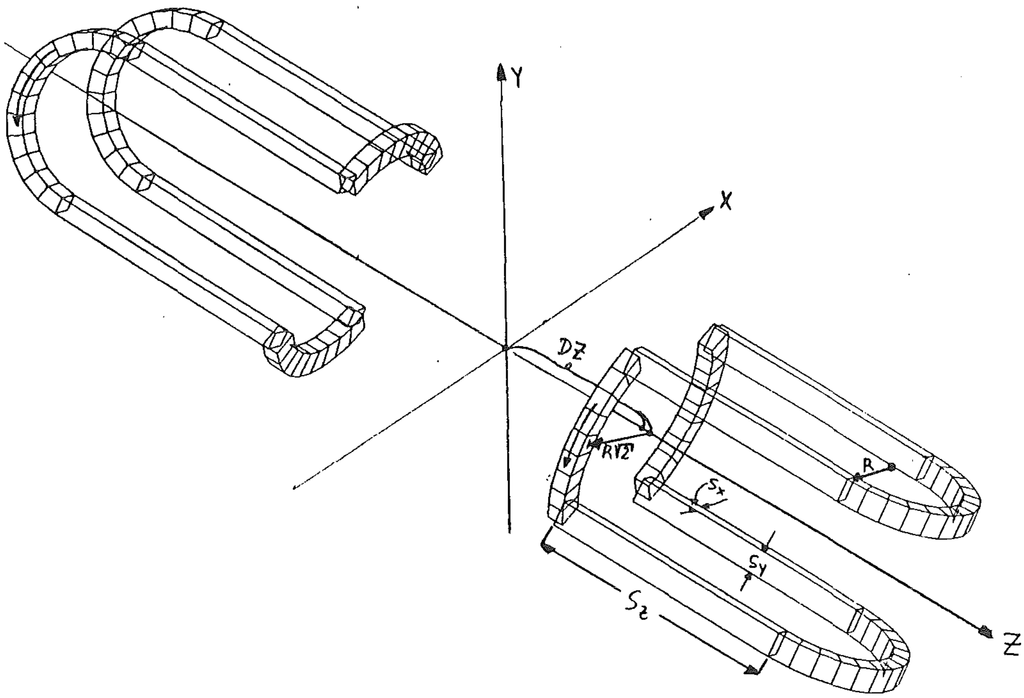
Z = Z-position of the center of the bars
R_1 = Radius at the smaller value of Z
R_2 = Radius at the right
S_R = Width in radial direction
S_Θ = Width in (azimuthal) Θ-direction
S_L = Axial length of the bars
J = Current density (direction shown by arrows)

The conversion between IOFFE input and CONE input is as follows:

	IOFFE	R,	Z,	HL,	45^0,	S_R,	S_Θ,	J $
→	CONE	Z,	R,	R,	S_R,	S_Θ,2(HL),		J $
	IOFFE	R,	Z,	HL,	-45^0,	S_R,	S_Θ	J $
→	CONE	Z,	R,	R,	S_R,	S_Θ,2(HL)		-J $

4.14 VARIATION OF IOFFE BAR

Call: IBOB R, DZ, S_x, S_y, S_z, J $



R = Radius (center line) of arcs whose planes are parallel to the XZ-plane on the positive figure.

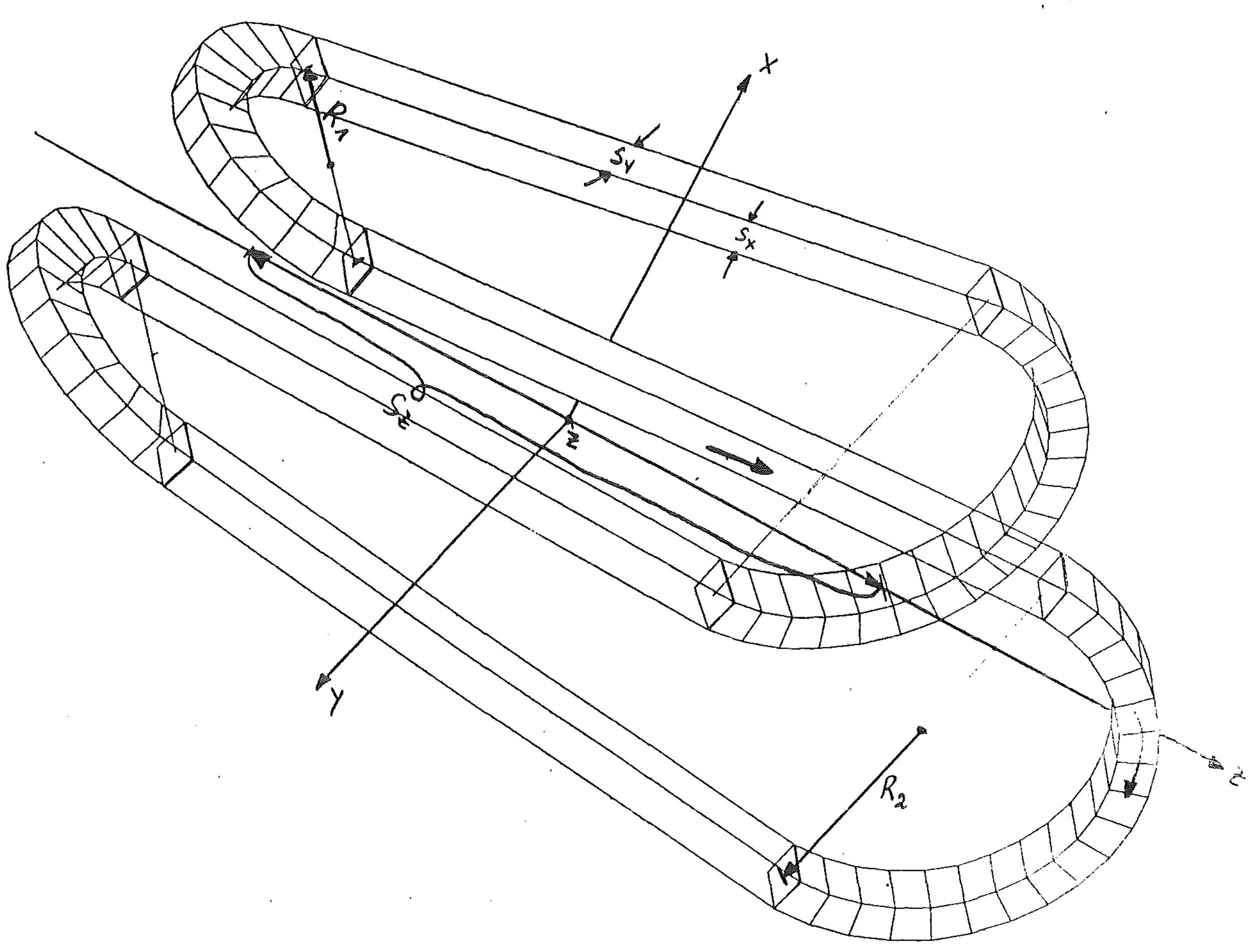
Note that the arcs whose plane is parallel to the XY-plane have a radius of $R \cdot \sqrt{2}$

DZ = Distance from the origin along the Z-axis to the center of the arcs whose radius is $R \cdot \sqrt{2}$

S_x = Cross section dimension in the X-direction for the bars
S_y = Cross section dimension in the Y-direction for the bars
S_z = Length of the bars
J = Current density (direction shown in the figure)

4.15 A CONE RELATED COIL

Call: JAW Z, R_1, R_2, S_x, S_y, J $



Z = Z-position of coil center

R_1 = Radius of the arc on the negative Z-end of the coil

R_2 = Radius of the arc on the positive Z-end of the coil

S_x = Cross section dimension in X-direction

S_y = Cross section dimension in Y-direction

S_z = Z-extent of the bars

J = Current density (direction shown by arrows)

Restriction:

$$SX > |R_2-R_1|$$

4.16 SPECIAL TMX-U COILS PRTZP AND PRTZN

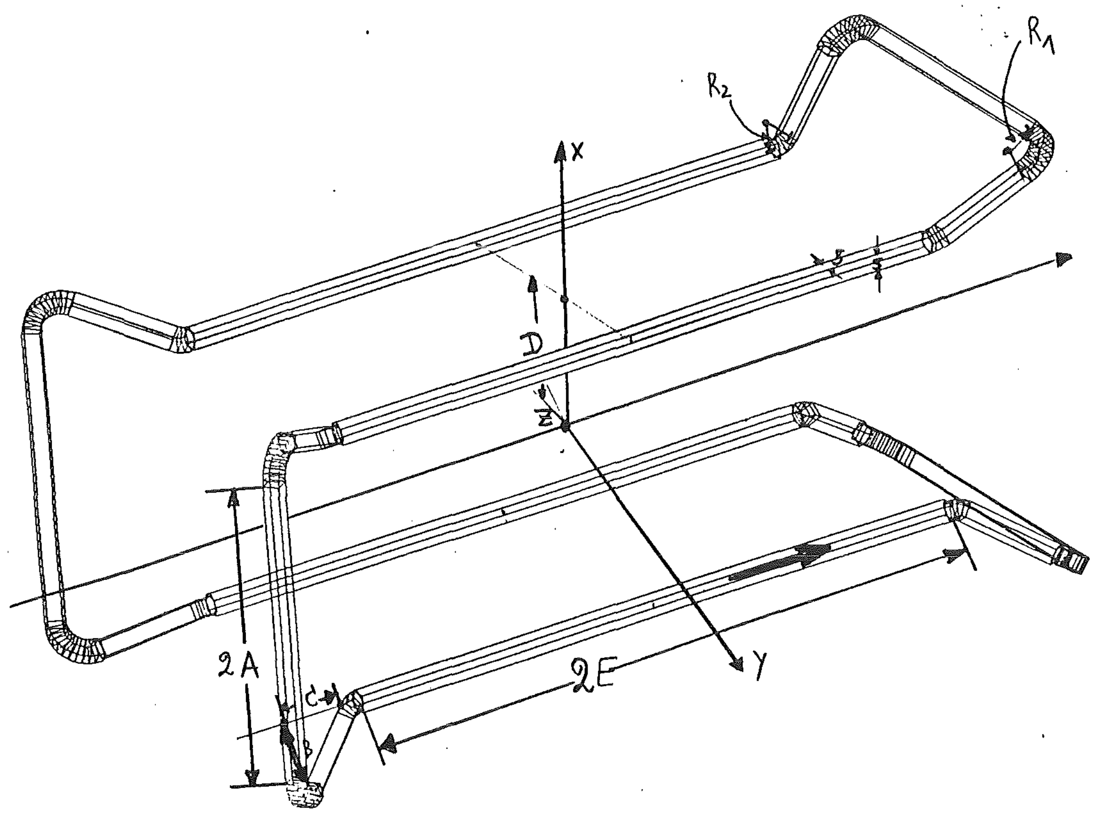
Call:

```
PRTZP  A, B, C, D, E, Z, R1, R2, S, J $
PRTZN  A, B, C, D, E, Z, R1, R2, S, J $
```

The PRTZP coil was created for the TMX-Upgrade machine. The restrictions on the parameters are as follows:

$$A \neq D ; \qquad B \neq 0 ; \qquad C \neq 0$$

The radii R_1 and R_2 must allow a straight section between the Z-direction bars and the X (or Y)-direction bars.
The coil has 16 GCE's and 16 arcs.
The PRTZN coil results from the PRTZP being rotated by 90^o around the Z-axis.



A = Half length of end bar
B = Flare out distance of outer bar
C = Z-component of outer bar

D^* = Half distance between Z-direction bars

E = Half length of Z-direction bars

Z = Z-position of center of coil

R_1 = Outer radius of curvature

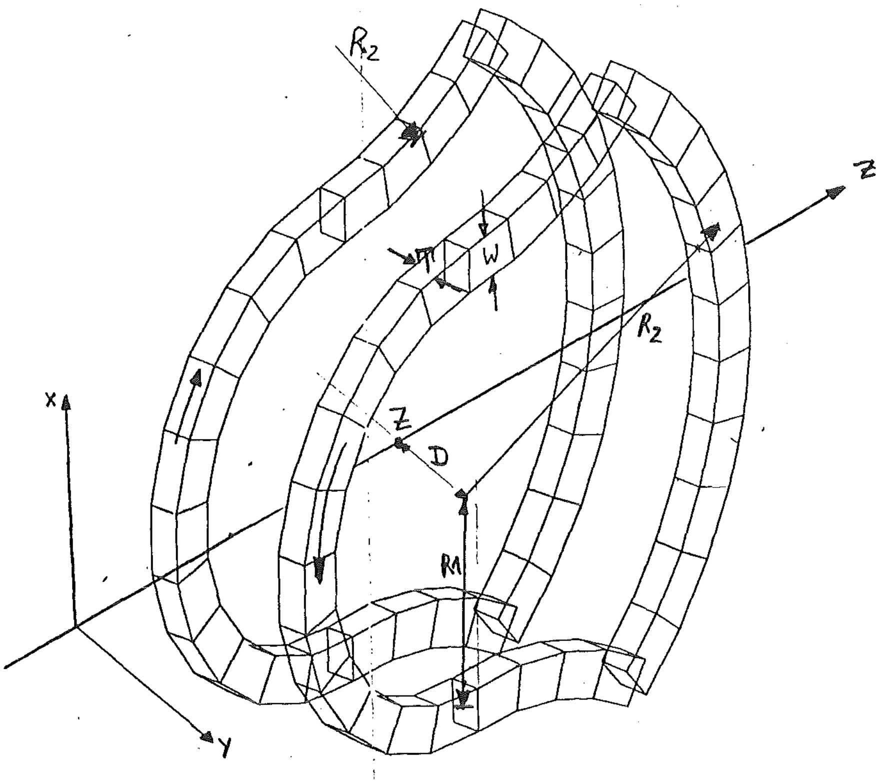
R_2 = Inner radius of curvature

S = Width of cross section (Square!)

J = Current density (direction shown by arrows)

4.17 BOW COIL(S)

Call: BOW Z, D, R_1, R_2, W, T, J $



Z = Z-position of center of all arcs

D = Half of the y-distance between the two coils

R_1= Radius of "small" arc

R_2= Radius of "big" arc

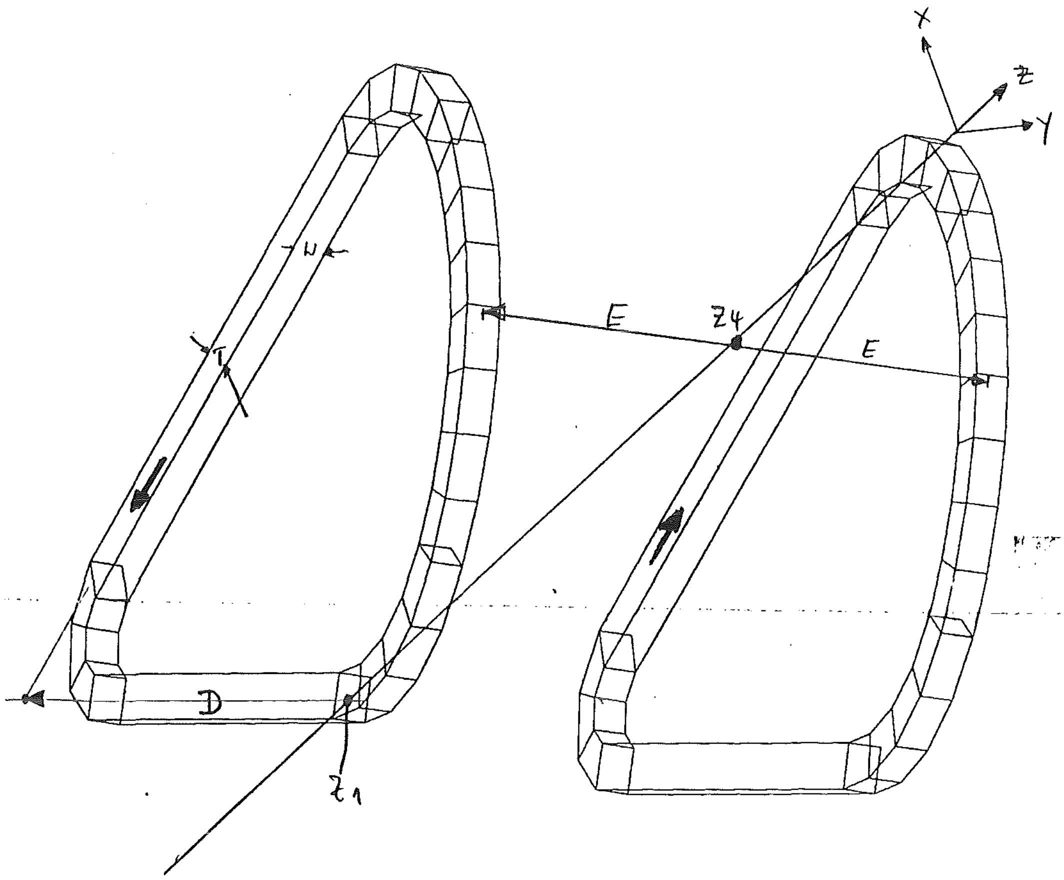
W = Width in x-direction

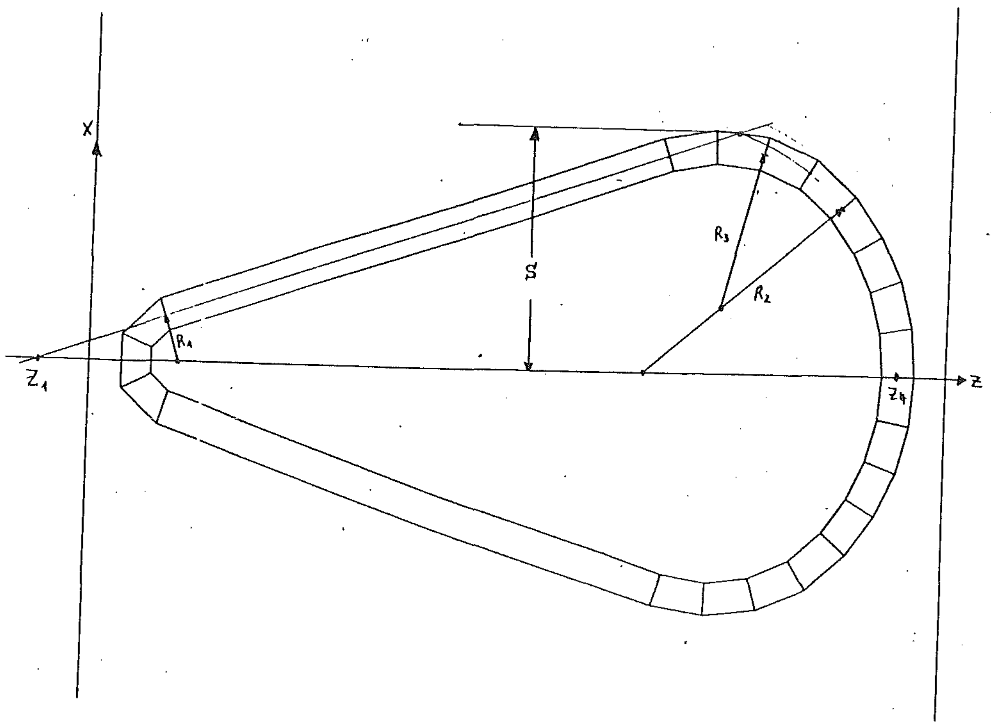
T = Width in y-direction

J = Current density (direction shown by arrows)

B O W L - C O I L (S)

Call: BOWL Z_1, Z_4, S, R_1, R_2, R_3, D, E, W, T, J $\not{S}$

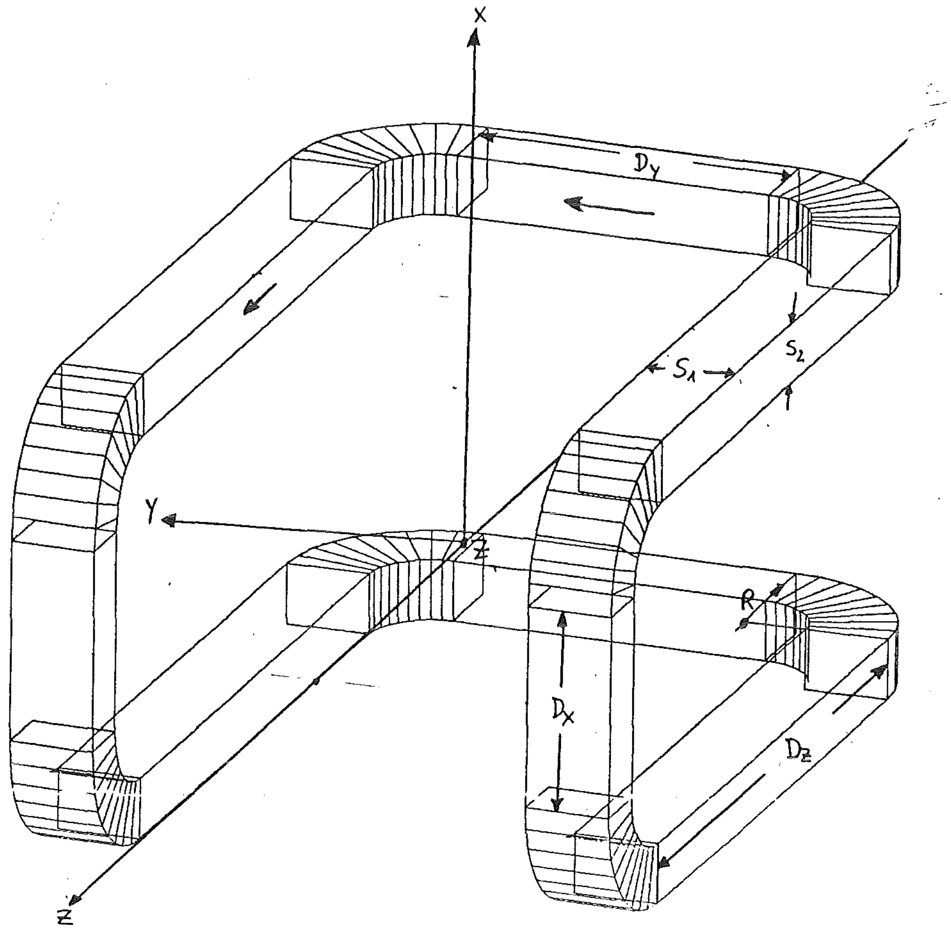




Z_1 = Left side z-position
Z_4 = Right side z-position
S = Half heigth
R_1 = Left radius
R_2 = Right radius
R_3 = Upper radius
D = Half distance between coils in the Y-direction at z_1
E = Half distance between coils in the Y-direction at z_4
W = Thickness in Y-direction
T = Thickness in X-direction
J = Current density (direction shown by arrows)

4.18 B O X - C O I L

Call: BOX Z, D_x, D_y, D_z, R, S_1, S_2, J $



Z = Z-position of center of coil

D_x = Length of straight section in X-direction

D_y = Length of straight section in Y-direction

D_z = Length of straight section in Z-direction

R = Radius of connecting arcs

S_1 = Width in Y-direction

S_2 = Width in X-direction

J = Current density (direction shown by arrows)

Restriction: D_x, D_y, D_z $\neq 0$

5. Tables of Calls

Table of Calls: 1

Name of coil(s)	Type	Input Parameter	Number of generated			
			Coils	LOOP's	ARC's	GCE's
Solenoid	SOL	Z, A, W, T, J	1	1	-	-
Equidistant Solenoids	SOL	Z, A, W, T, J, Δc, N.	N	N	-	-
BITTER-Coil	BIT	Z, A, W, T, N., J_1	1	N	-	-
Race-Track Coil	RT	Z, H, S, θ_x, W, T, J	1	-	2	2
Window Frame Coil	WFX	Z, C, DZ, DP, R, S1, S2, J	2	-	8	8
	WFY	Z, C, DZ, DP, R, S1, S2, J	2	-	8	8
	WFZ	Z, DX, DY, R, S1, S2, J	1	-	4	4
YIN-YANG Coil	YY	R_2, R_1, H, DZ, W, T, J	2	-	8	-
	YYN	R_2, R_1, H, DZ, W, T, J	1	-	4	-
	YYP	R_2, R_1, H, DZ, W, T, J	1	-	4	-
Elongated YIN-YANG Coils	EYY	R_2, R_1, DL, DZ, W, T, J	2	-	8	8
	EYYN	R_2, R_1, DL, DZ, W, T, J	1	-	4	4
	EYYP	R_2, R_1, DL, DZ, W, T, J	1	-	4	4
	EYYZ	R_2, R_1, DL, DZ, W, T, J	2	-	8	8

Table of Calls: 2

Name of coil(s)	Type	Input Parameter	Number of generated			
			Coils	LOOP's	ARC's	GCE's
C-shaped Coils	CEE	R_2, R_1, H, DZ, Θ_z, W, T, J	2	-	12	4
	CEEN	R_2, R_1, H, DZ, Θ_z, W, T, J	1	-	6	2
	CEEP	R_2, R_1, H, DZ, Θ_z, W, T, J	1	-	6	2
	CEEZ	R_2, R_1, H, DZ, Θ_z, W, T, J	2	-	12	4
Reversed C-shaped Coils	RC	R_2, R_1, H, DZ, Θ_z, W, T, J	2	-	12	4
	RCP	R_2, R_1, H, DZ, Θ_z, W, T, J	1	-	6	2
	RCN	R_2, R_1, H, DZ, Θ_z, W, T, J	1	-	6	2
	RCZ	R_2, R_1, H, DZ, Θ_z, W, T, J	2	-	12	4
Squeezable C-shaped Coils	CES	Z, DZ, R_1, R_2, H_1, H_2, Θ_z, W, T, J	2		12	4
	CESP	Z, DZ, R_1, R_2, H_1, H_2, Θ_z, W, T, J.	1		6	2
	CESN	Z, DZ, R_1, R_2, H_1, H_2, Θ_z, W, T, J	1		6	2
Squeezable Reversed C-shaped Coils	RCS	Z, DZ, R_1, R_2, H_1, H_2, Θ_z, W, T, J	2		12	4
	RCSP	Z, DZ, R_1, R_2, H_1, H_2, Θ_z, W, T, J	1		6	2
	RCSN	Z, DZ, R_1, R_2, H_1, H_2, Θ_z, W, T, J	1		6	2

Table of Calls: 3

Name of coil(s)	Type	Input Parameter	Number of generated			
			Coils	LOOP's	ARC's	GCE's
C-shaped Coils with extended big arcs	CNEW	Z, DZ, H, R_2, R_1, Θ_z, W, T, J	2	-	8	8
	CNEWP	Z, DZ, H, R_2, R_1, Θ_z, W, T, J	1	-	4	4
	CNEWN	Z, DZ, H, R_2, R_1, Θ_z, W, T, J	1	-	4	4
IOFFE-Bars	IOFFE	IRI, Z, HL, Θ_x, S_R, S_Θ, J	1	-	4	4
	IOFFE	-IRI, Z, HL, Θ_x, S_R, S_Θ, J	1	2	-	4
	IOFFR	R, Z, HL, Θ_x, S_R, S_Θ, RC, J	1	-	12	4
	EIGHT	R, Z, HL, Θ_x, S_R, S_Θ, J	1	-	8	8
Saddle Coils	SADL	R, Z, HL, Θ_y, α, S_R, S_Θ, J	2	-	4	4
	SADDLE	R, Z, HL, Θ_y, S_R, S_Θ, R_c, J	2	-	12	4
	SAD	Z, R, RA, Θ_L, Θ_s, S1, S2, S3, J	1	-	6	2
Four Bars	CONE	Z, R_1, R_2, S_R, S_Θ, S_L, J	(1)	-	-	4
Variation of IOFFE-Bars	IBOB	R, DZ, S_x, S_y, S_z, J	2	-	8	8
Cone related Coil	JAW	Z, R_1, R_2, S_x, S_y, S_z, J	1	-	4	4
TMX-Upgrade Coils	PRTZP	A, B, C, D, E, Z, R_1, R_2, S, J	1	-	16	16
	PRTZN	A, B, C, D, E, Z, R_1, R_2, S, J	1	-	16	16

Table of Calls: 4

Name of coil(s)	Type	Input Parameter	Number of generated			
			Coils	LOOP's	ARC's	GCE's
Bow Coils	BOW	Z, D, R_1, R_2, W, T, J	2	-	8	-
Bow related Coils	BOWL	Z_1, Z_4, S, R_1, R_2, R_3, D, E, W, T, J	2	-	8	4
Box Coil	BOX	Z, D_x, D_y, D_z, R, S_1, S_2, J	1	-	8	8

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