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Baseline Report

ITER Coordinate System and Coils Polarities

This document introduces a toroidal coordinate system convention that shall be used to define the current circulation in the ITER coils for design, modelling and control purposes. Starting from the definition of the coordinate system, the sign convention of the current flowing in each magnet is identified in a consistent way and the polarity of each coil is defined. The defined coil polarity is used to produce consistent and unambiguous labelling and physical connections of the power supplies to the magnets.

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Change Log			
ITER Coordinate System and Coils Polarities (QRUDS6)			
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v1.0	Signed	01 Oct 2015	
v1.1	Approved	18 Nov 2015	This version of the document implements all comment received by Joe Snipes.

Table of Contents

1 Purpose

This document introduces a toroidal coordinate system convention that shall be used to define the current circulation in the ITER coils for design, modelling and control purposes. Starting from the definition of the coordinate system, the sign convention of the current flowing in each magnet is identified in a consistent way and the polarity of each coil is defined. The defined coil polarity is used to produce consistent and unambiguous labelling and physical connections of the power supplies to the magnets.

2 Scope

This document applies to all ITER magnets.

3 Definitions

CC	Correction Coils
CS	Central Solenoid
IVCs	In-vessel Coils
PF	Poloidal field
PR	Project Requirements
PCS	Plasma Control System
TF	Toroidal field
TGCS	Tokamak Global Coordinate System
VS	Vertical Stability

4 References

1	ITER Coordinate Systems, IDM_D_2A9PXZ
2	M. Kocan, Magnetic field orientation in ITER, IDM_D_GGKFNP
3	M. Clough, Magnetic coil numbering conventions, IDM_D_N4MVG9 (v1.5)
4	Project Requirements (PR), IDM_ D_27ZRW8 (v5.3)
5	Y. Gribov, Progress on the ITER physics basis; Plasma Operation and Control, Nucl. Fusion (2007) 47 S385
6	P. Bauer, Feeder Electrical Polarity Schematic, IDM_D_R4A445, and N. Sato, IDM_D_QYFKLV, draft version 14 March 2015.

5 The main conventions

In order to avoid confusion it is important to follow as much as possible the standard conventions used either for the power supply design, the coil and plasma control systems as well as physics modelling and analysis.

5.1 The geometric co-ordinate system

The ITER co-ordinate system [1] defines the centre point of the ITER x-y-z co-ordinate system as the centre of the torus, with z=0 at the torus mid-plane, and positive z upwards. The TGCS is rotated on the Z axis in counter clockwise direction precisely by 37.0º degrees relative to the Geographic North, with the y-axis pointing in northern direction (323.0º) and the x-axis in eastern direction (to 37.0º). The TF coil 01 is positioned parallel to the positive x-axis. This is the co-ordinate system used within the CATIA system for ITER design.

This co-ordinate system directly connects to the toroidal co-ordinate system given in figure 1 with the radial axis, R, pointing outward, the z-axis upward, and the toroidal angle ϕ, as shown (i.e. counter clockwise seen from above/in negative z-direction). Furthermore, a minor radius, r, and a clockwise poloidal angle θ, with θ=0 defined as the angle between the x-axis and the radial at the inside of the torus. The origin of the torus, at R_o = 6.2m, z = 0m, θ = 0 and ϕ = 0.

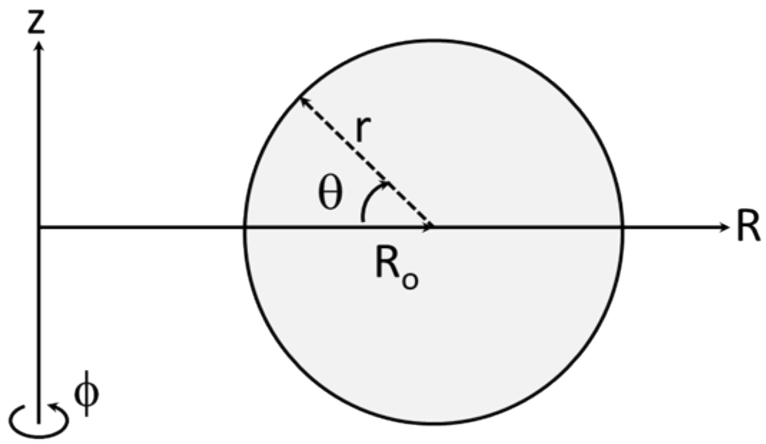


Figure 1: *The toroidal co-ordinate system.*

The R, r, z and ϕ definitions are all standard. However, sometimes the poloidal angle θ may be defined differently than presented here. For example, one could also define it simply as the angle between the toroidal direction and the magnetic field lines [2]. It is important that, in the representation shown in figure 1, the poloidal angle is defined, with an origin (θ=0) and a clear direction. The direction follows the helicity of the ITER field-lines, in positive poloidal direction, when moving in positive toroidal direction. Also, the definition of poloidal angle presented here, follows the ordering/numbering of the poloidal field coils (see figure 6) as well as the magnetic coil numbering convention [3]. Note that the numbering of the TF coils as well as other coil systems follows the logical start and direction of the co-ordinate system, with TF01, at y=0, and the increment going in counter clockwise (i.e. positive ϕ) direction, as shown in figure 2.

The co-ordinate system translates to the TGCS as:

$x = (R_o - r\cos\theta)\cos\phi$
□$y = (R_o - r\cos\theta)\sin\phi$
□$z = r\sin\theta$

for the toroidal coordinate system, and as:

$x = R\cos\phi$
□$y = R\sin\phi$
□$z = z$

for the cylindrical coordinate system.

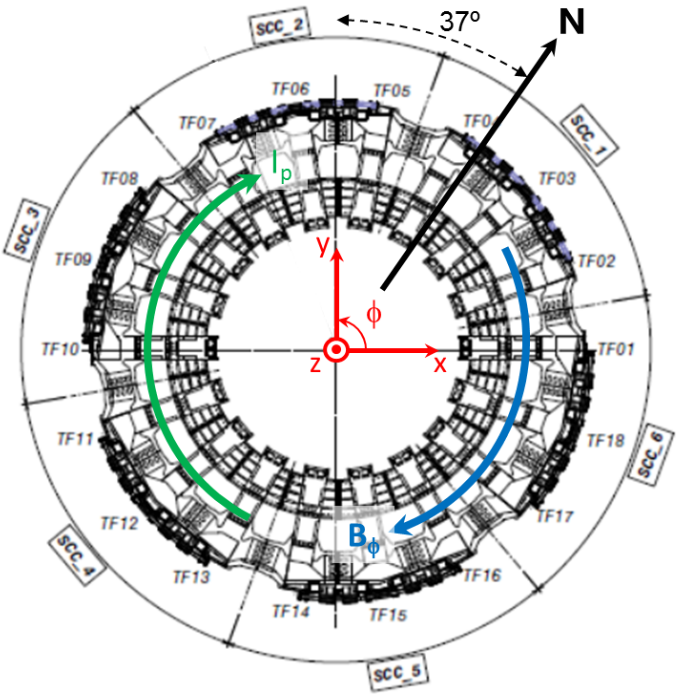


Figure 2: *The numbered TF and CC coils within the TGCS, as seen from above, with the y-axis vertical and the positive x-axis pointing towards the right. The y-axis is rotated by 37° around the z-axis with respect to the geographic north.*

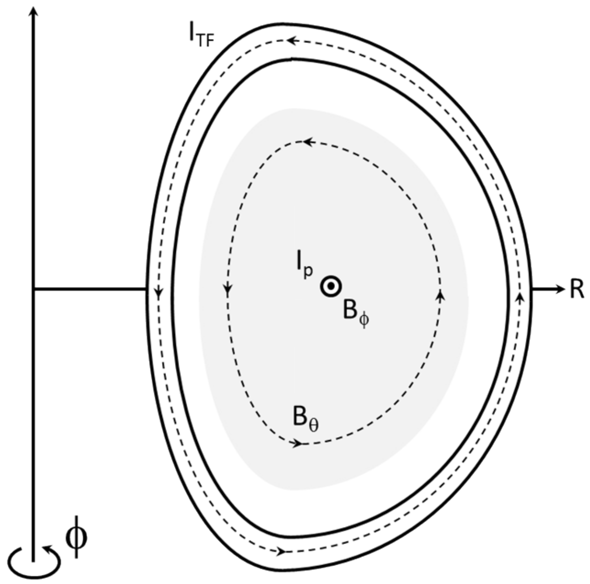
TF01 is aligned with the positive x-axis and the numbering of the TF, as well as the CC coils increment in positive direction, i.e. counter clockwise.

The direction of the ITER plasma current (I_p in green) and toroidal magnetic field (B_ϕ in blue) are given, as defined by the project requirements, within the ITER toroidal coordinate system and TGCS.

5.2 The ITER project requirements

The ITER PR [4] states: '*The reference directionality of the toroidal current and field shall be as follows: plasma current in the clockwise direction looking from above with the same direction for the toroidal field,* ....'. Using the standard toroidal co-ordinate system introduced in the previous section, both the plasma current and the toroidal magnetic field are in the counter (i.e. negative) ϕ direction. In other words, the plasma current and the magnetic field produced by the TF coils have negative toroidal components (see figure 2 and figure 3).

Figure 3: *The plasma current (I_p) and toroidal magnetic field (B_ϕ), shown in the poloidal plane, with the TF coil current and poloidal magnetic field in counter clockwise direction, down on the inside of the torus, for a negative plasma current and magnetic field (pointing out of the plane).*

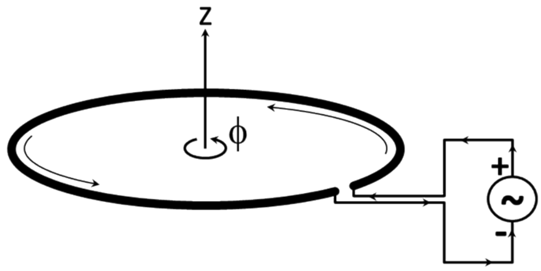


5.3 Power supply, coil current and control conventions

A positive current is defined as flowing from the positive to the negative side of the power supply. Similarly for a coil, the current flows from the positive to the negative. A positive voltage increases a positive current and decreases a negative current.

Regarding control, it should be considered that it is more logical to control a negative current by a negative power supply voltage hence a more negative voltage request leads to a more negative (according to the geometric co-ordinates) current in the coil. This is especially important for those currents that will be actively controlled by the PCS. Figure 4 shows that both conventions can be met with the right connections.

Figure 4: *A positive current, generated by a positive power supply voltage, in the electrical circuit is equivalent to a positive current in the geometric co-ordinate system.*



5.4 Conventions regarding radial magnetic fields

It will be shown later that the above conventions are not sufficient. This is for example the case when radial magnetic fields are generated, for which the coil or circuit current direction may not obey the above conventions. In this case, where possible, it is assumed that a positive power supply voltage (and power supply current) should generate a positive radial magnetic field, i.e. radially outward (away from the plasma centre). It is best to discuss these details per case, which is done below.

6 The polarities of the various coils

6.1 The TF circuit

The TF power supplies are unidirectional; hence the current cannot be reversed. Figure 5, shows the direction of the TF coil current, with a positive current flowing from positive to negative, generating a magnetic field out of the page. According to the co-ordinate system shown in figure 1, this is however a negative TF current generating a negative toroidal magnetic field. Although confusing, the unidirectional nature of the power supply, is unlikely to cause control problems. A positive voltage on the TF coils results in a negative toroidal field.

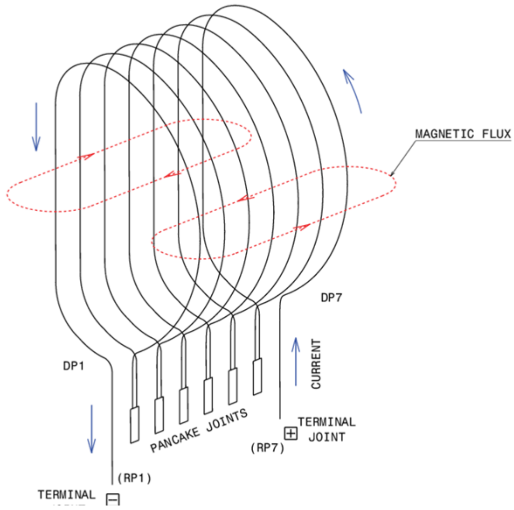


Figure 5: *In the above picture the current flows in the positive direction, according to the power supply convention, however in the negative direction according to the geometric co-ordinate system.*

6.2 The PF and CS circuits

Figure 6 depicts the PF and CS coil current directions, at a given time of the discharge during the plasma current flattop, with respect to the plasma current, for a standard ITER configuration. Note that this may differ during plasma initiation or other phases of the discharge. The arrows indicate the direction of the magnetic field. The plasma current is pointing out of the plane, which is opposite to the direction of the positive toroidal co-ordinate in the standard toroidal co-ordinate system (Figure. 1). This corresponds to a negative plasma current.

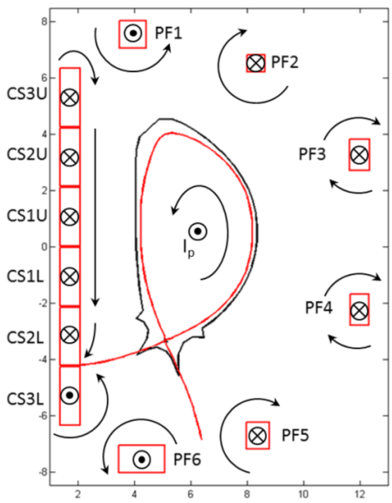


Figure 6: *The PF and CS coil current directions with respect to the plasma current, for a standard ITER flattop configuration. Note that this may differ during plasma initiation or other phases of the discharge. The arrows indicate the direction of the magnetic field. The plasma current is pointing out of the plane, which is opposite to the direction of the toroidal co-ordinate in the standard toroidal co-ordinate system.*

To comply with both the power supply and standard co-ordinate conventions, the coils should be connected, as shown in figure 7, with the current flowing in a positive direction (i.e. counter clockwise from above). This will ensure that:

> A positive voltage on the power supply will hence generate a more positive current in the PF coils.

Similarly the CS coils should be connected, as shown in figure 7, with the current flowing in a positive direction (i.e. counter clockwise from above). This will ensure that:

> A positive voltage on the power supply will hence generate, in the CS coils, a more positive current according to the geometric and power supply conventions.

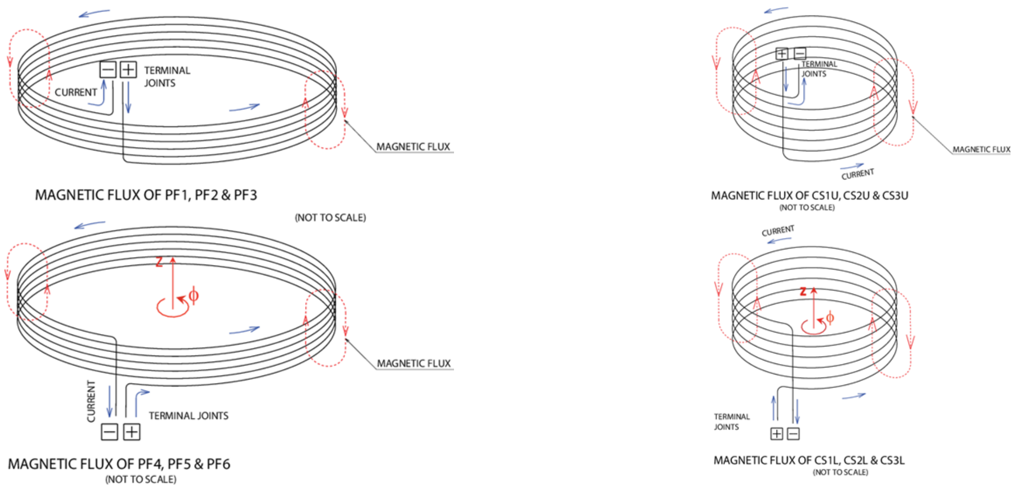


Figure 7: (left) *The polarity and positive current direction for the PF coils.* (right) *The polarity and positive current direction for the CS coils.*

6.3 The vertical stabilization circuits

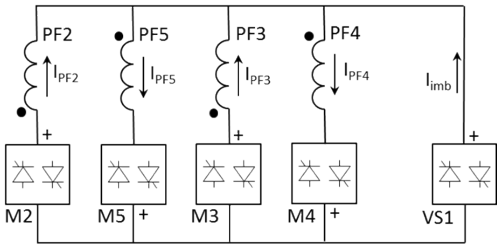
The radial magnetic field component is used to control the vertical position of the plasma and to ensure vertical stability [5]. The main convention for these circuits is that positive power supply voltage in the VS systems (circuits) should generate currents that produce a positive major radial component of the magnetic field in the vacuum vessel in the co-ordinate system shown in figure 1. That is, a field that points in the major radial direction. At ITER, different circuits will provide vertical position and stability control, VS1, VS2 and VS3.

The VS1 circuit produces an imbalance between the upper and the lower PF coils, providing a radial component of magnetic field in the vacuum vessel for plasma vertical position control. As shown in figure 8, a positive voltage of the VS1 power supply decreases the currents in the upper coils (PF2 and PF3) and increases those in the lower coils (PF4 and PF5), generating a positive imbalance current defined as:

$$I_{IMB}^{VS1} = I^{lower}_{PF} - I^{upper}_{PF} = I_{PF4} + I_{PF5} - I_{PF2} - I_{PF3}$$

as shown in figure 8 (right) with:

> A positive VS1 voltage and a positive imbalance current, generates a positive radial magnetic field (i.e. outward in the major radial direction) in the vacuum vessel.



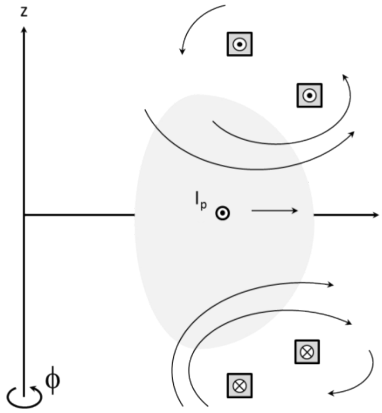


Figure 8: (left) *The vertical stabilization circuit VS1: VS1 is the vertical stabilization converter; M2 to M5 are the main converters for the coils PF2–PF5. Note that this figure differs from the circuit shown in ref. [5] with respect to the sign/direction of the imbalance current.* (right) *For the four PF coils the imbalance current direction is shown. A positive, radially outward, magnetic field generated by a positive VS1 imbalance (I_{imb}>0, i.e. a larger current in the lower coils compared to the current in the upper coils).*

VS2 will make use of the upper and lower CS2 coils. Similar as with VS1, a positive outward radial magnetic field is generated if the lower coil current is larger than the upper coil current, thus:

$$I_{IMB}^{VS2} = I_{CS2L} - I_{CS2U}$$

With the circuit connected as shown in figure 9. This will ensure that a positive VS2 voltage, results in a larger (more positive) VS2 imbalance current, yielding a more positive radial magnetic field in geometric co-ordinates.

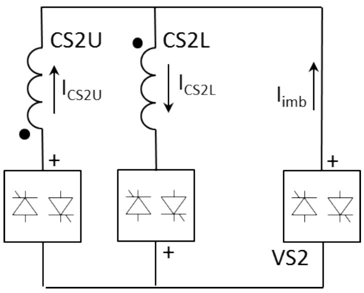


Figure 9: *The vertical stabilization circuit VS2 generating a positive imbalance between CS2L and CS2U to induce a positive (i.e. major radially outward) magnetic field.*

Figure 10 shows the VS3 circuit (VS in-vessel coils), which for a positive power supply current will have opposite current in the upper and lower coils, hence, the current direction is ambiguous in the geometric co-ordinate system.

The circuit should be connected such that a positive power supply current generates a positive radial magnetic field, as highlighted in figure 10.

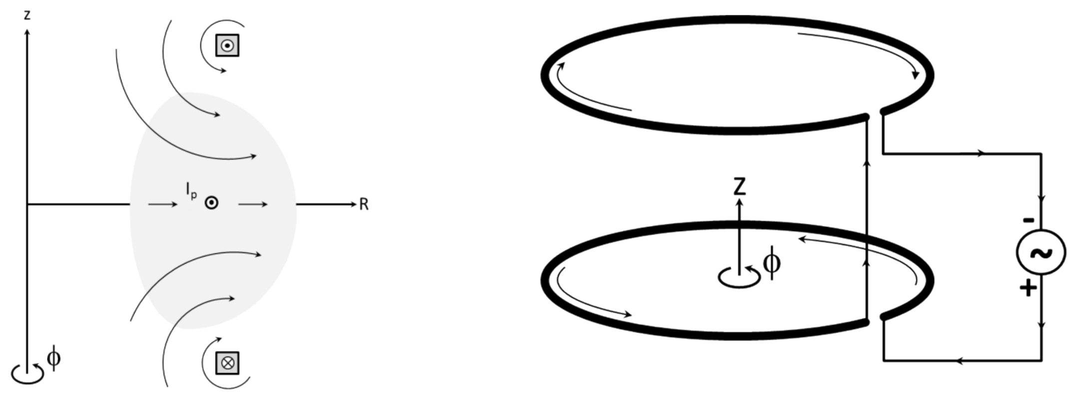


Figure 10: (left) *The direction of the actual currents in VS3 to produce a positive radial magnetic field in the vacuum vessel.* (right) *The VS3 power supply connection to produce the situation as shown on the left.*

6.4 The CC coils

The error field correction coils (CC) are connected in opposite pairs, such that both produce a magnetic field in the same direction (in xyz co-ordinates (Figure 2)). Therefore it is not possible to have coil currents with a definite direction in the geometric co-ordinate system as well as a definite direction of the radial magnetic field generated by the coils. A special convention for these coils has to be defined.

There are 3 pairs of 6 side correction coils (SCCs) in the mid-plane (see figure 11 (left), and the same at the top (TCC) and the bottom (BCC) of the device (see figure 12). The first 3 coils (xCC_1, xCC_2 and xCC_3), counting from the x-axis in positive toroidal direction (see figure 2), are connected in series to the 3 opposite coils (xCC_4,xCC_5 and xCC_6).
The following convention is assumed:

> For the first 3 coils, a positive power supply voltage generates current that produces a magnetic field pointing away from the plasma (center) in the area closest to the coil 'centre'. As a consequence, the opposite coil of each pair will produces a magnetic field pointing towards from the plasma (center) in the area closest to this coil 'centre'.

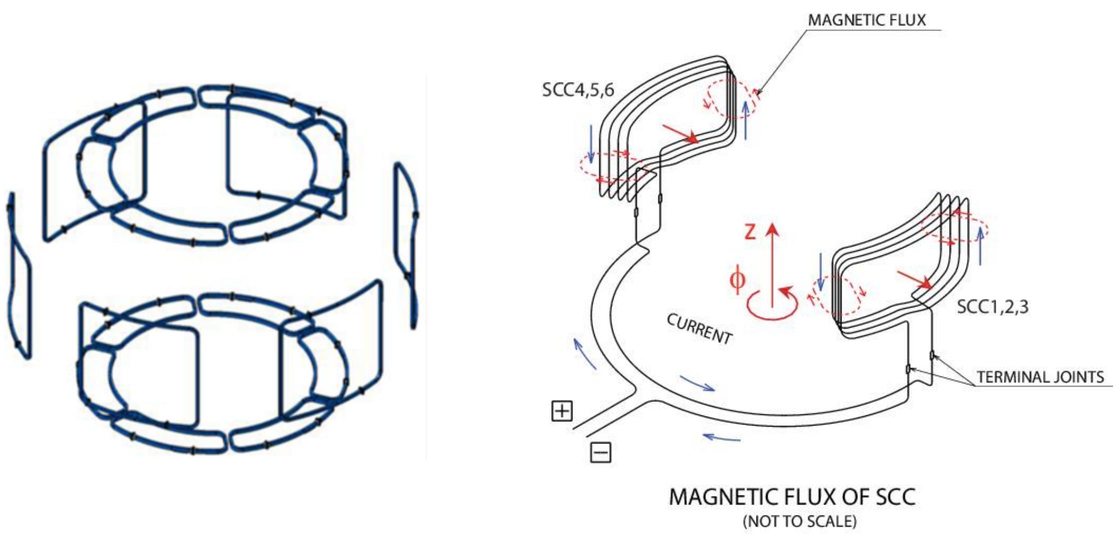


Figure 11: (left) *Schematic picture of the ITER CC coils, with the SCCs in the mid-plane, the TCCs at the top and BCCs at the bottom.* (right) *The connection of a SCC coil pair, with an outward radial magnetic field for the coil SCC1,2 or 3, and an inward magnetic field for the opposite coil of the pair. This is changed with respect to ref. [6].*

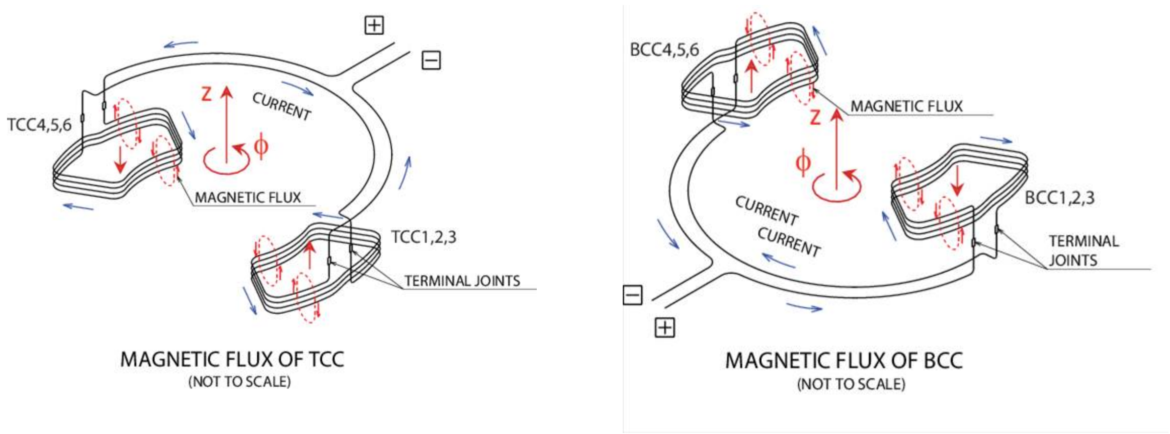


Figure 12: (left) *The connection of a TCC coil pair, with an upward (away from the plasma) radial magnetic field for the coil TCC1,2 or 3, and a downward magnetic field for the opposite coil of the pair.* (right) *The connection of a BCC coil pair, with a downward (away from the plasma) radial magnetic field for the coil BCC1,2 or 3, and a upward magnetic field for the opposite coil. These are unchanged with respect to ref [6].*

6.5 The ELM coils

Besides the VS3 in-vessel coil system, there are the IVCs for ELM control. These have each independent power supplies. These should be connected simply in such a way that a positive power supply voltage generates current producing the normal to the plasma boundary component of the magnetic field directed out of the plasma in the area closest to the coil 'centre'.

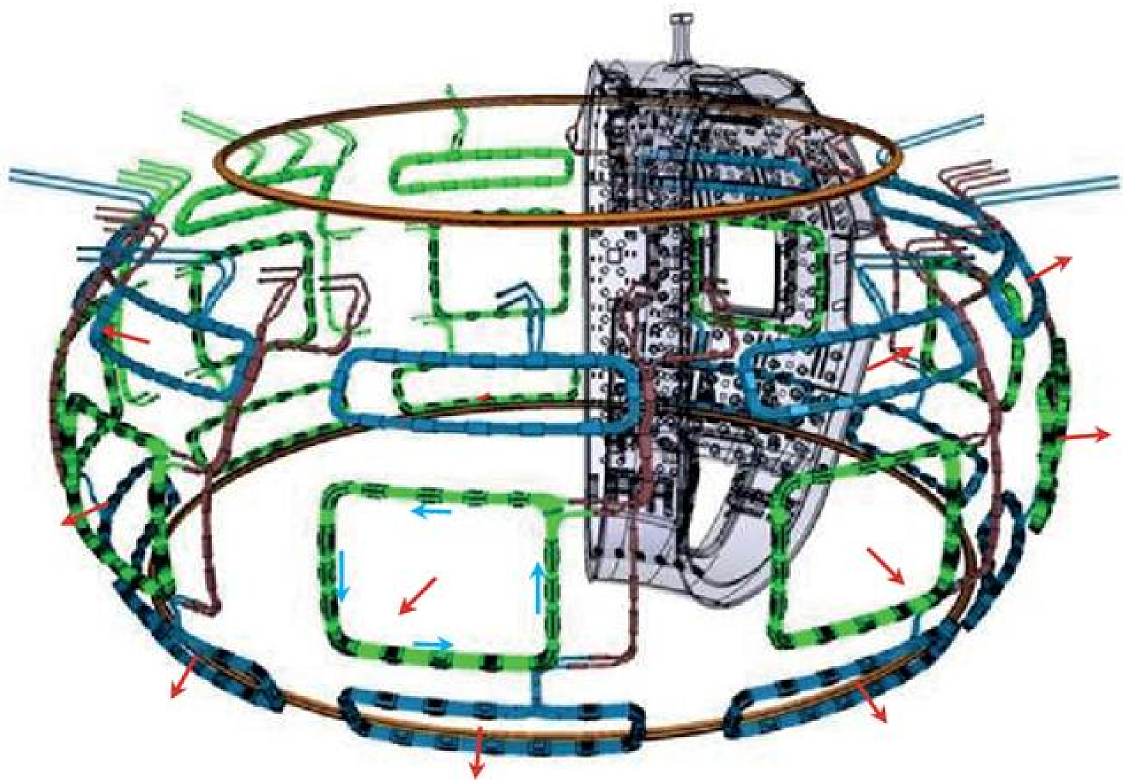


Figure 13: *ELM coils positive current convention (highlighted by the light blue arrows in the Figure) and associated magnetic field (represented by the red arrows).*