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# Performance analysis of Rogowski coils and the measurement of the total toroidal current in the ITER machine

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## Abstract

The paper carries out a comprehensive study of the performances of Rogowski coils. It describes methodologies that were developed in order to assess the capabilities of the Continuous External Rogowski (CER), which measures the total toroidal current in the ITER machine. Even though the paper mainly considers the CER, the contents are general and relevant to any Rogowski sensor.

The CER consists of two concentric helical coils which are wound along a complex closed path. Modelling and computational activities were performed to quantify the measurement errors, taking detailed account of the ITER environment. The geometrical complexity of the sensor is accurately accounted for and the standard model which provides the classical expression to compute the flux linkage of Rogowski sensors is quantitatively validated. Then, in order to take into account the non-ideality of the winding, a generalized expression, formally analogue to the classical one, is presented. Models to determine the worst case and the statistical measurement accuracies are hence provided. The following sources of error are considered: effect of the joints, disturbances due to external sources of field (the currents flowing in the poloidal field coils and the ferromagnetic inserts of ITER), deviations from ideal geometry, toroidal field variations, calibration, noise and integration drift.

The proposed methods are applied to the measurement error of the CER, in particular in its high and low operating ranges, as prescribed by the ITER system design description documents, and during transients, which highlight the large time constant related to the shielding of the vacuum vessel.

The analyses presented in the paper show that the design of the CER diagnostic is capable of achieving the requisite performance as needed for the operation of the ITER machine.

**Keywords:** Rogowski coil, current sensor, statistical measurement error, ITER CER, ferromagnetic inserts, integration drift, calibration

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## 1. Introduction

On contemporary fusion research facilities based on magnetic confinement, primary control of the machine is based on measurements of the magnetic field surrounding the core of the device. This approach will also be applied on ITER, the tokamak device currently under construction in Cadarache, France, aimed at demonstrating the viability of commercial energy production.

As part of the suite of magnetics measurements on ITER, a Rogowski coil (also known as Chaddock-Rogowski coil) [1–7], the Continuous External Rogowski (CER), is included to determine the current flowing in the plasma core and machine structures. This measurement is of high importance due to the very large electromagnetic energy

associated with the current in the plasma core. Specifically, the CER provides a measurement of the total toroidal current  $I = I_p + I_{\text{eddy}}$ , where  $I_p$  is the plasma current and  $I_{\text{eddy}}$  is the current induced in the passive structures threading with the CER itself [8–10]. A number of diagnostic systems contribute to the accurate measurement of the plasma current and the toroidal current in ITER: in-vessel and outer vessel coils, high frequency coils, steady-state sensors, continuous flux loops, the CER and the Fiber Optic Current Sensor. In particular, the in-vessel tangential coils set provide the reference estimate of  $I_p$  for operation. The key role of the CER is to provide a supplementary measure of the toroidal current in quiescent (flat-top) situations, with a single sensor in an uncomplicated, stable, radiation-tolerant and relatively direct fashion, so that it is suitable for ensuring the integrity of the measurement of  $I_p$ . For this reason it is an important part

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in the provision of a safety-relevant measurement of  $I_p$ , whose range will be prescribed in the ITER operating license [9]. This role will be integrated within the plasma control system of the machine [9, 11].

The paper addresses a thorough performance assessment of Rogowski coils. It develops by taking the CER as main working example, but the discussed techniques are general and relevant to any application involving Rogowski sensors. Modelling and computational activities are described, which allow to quantify the measurement errors, taking detailed account of the environment. The geometrical complexity of the sensor is accurately accounted for and the standard model which provides the classical expression to compute the flux linkage of Rogowski sensors [4] is considered and quantitatively validated. In order to take into account the non-ideality of the winding, a generalised formula, formally analogue to the classical one, is presented (eq. (6)). Models to determine the worst case and statistical measurement accuracies are then provided, which consider the following sources of error:

- approximation of the flux linkage with a discrete sum of fluxes linked with circular turns,
- effects of the joints,
- effects of nearby ferromagnetic components (the ferromagnetic inserts of ITER [12]),
- effects of the eddy currents,
- deviations from ideal geometry of the sensor's windings (deformation and misalignment of the turns, and centricity effect),
- disturbances due to external sources of field (the currents flowing in the poloidal field coils),
- effects of the non ideal geometrical configuration of the threading and non-threading current carrying conductors (calibration using poloidal field coils),
- effect of the toroidal field variations,
- nuclear-induced noise, electronic noise, integration drift.

Within this framework, the measurement error is evaluated, with the aid of a number of suitable operating reference scenario.

The target CER specification define the maximum measurement error in statistical terms as twice the standard deviation  $\sigma$ , in two different operating ranges [10]:

$$2\sigma_{\max} = \begin{cases} 1\%, & \text{if } 1\text{ MA} \leq I \leq 20\text{ MA} & \text{high range,} \\ 10\text{ kA}, & \text{if } I \leq 1\text{ MA} & \text{low range.} \end{cases} \quad (1)$$

The analyses that follow show that such specifications can be met.

## 2. The CER sensor

A CER sensor is constituted of two halves, the inboard and the outboard parts, each of which consists of two concentric helical windings and is assembled in the form of a

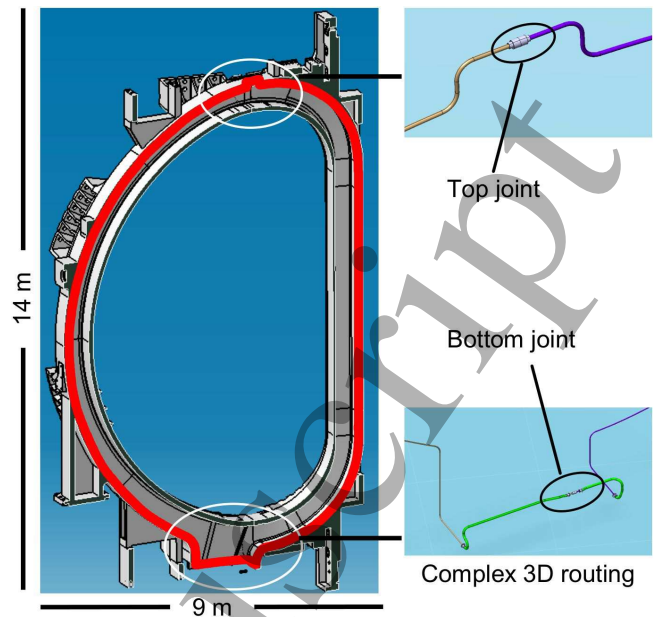


Figure 1: Routing of the CER sensor (bold red line) in a groove cut in the TF coil casing. The insets highlights the complexity of the path. The top joint only has mechanical function, while from the bottom one the two shielded twisted pairs which carry the output signals of the inboard and the outboard part of the sensor emerge.

cable. The two cables are positioned in a groove cut in the casing of a toroidal field (TF) coil on its outer perimeter, along a complex path (Fig. 1) designed as a sequence of straight segments and circular arcs [13]. The ends of the two cables are joined together by means of a top and a bottom mechanical joint. The ITER machine will be equipped with three CER sensors, mounted at different octants, 120 degrees apart toroidally [8]. Figure 2 shows a typical Rogowski coil of the same type of the CER, namely made of two parts and with a double-layer winding. In particular, the electrical connection between the inboard and the outboard windings is accomplished in the bottom joint, while the top joint has mechanical function only. The two half coils are put in series, with the proper polarity. In the case of the CER however, the inner windings of the inboard and outboard parts are not electrically connected in the bottom joint. In fact, for calibration purposes (§ 13) and for possible use of one half in case of failure of the other half, the two parts are considered as individual sensors. That is to say, instead of realising the electrical connection in the joint, the two halves are put in series by switches in the data acquisition card, when the diagnostic is operating in measure mode (rather than calibration or other service modes).

The main design specifications and derived parameters of the CER, which were considered for the studies reported in this article, are detailed in Tab. 1. In the final design the routing has been slightly modified in the lower region (the feedout region), including the location of the bottom joint. Such changes do not have any significance with respect to the results we report, as it will be clear from the analyses

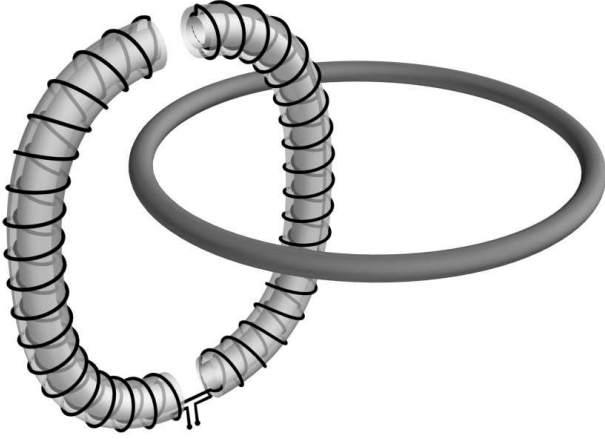


Figure 2: A typical Rogowski coil made of two halves. For convenience of illustration, the windings are represented with a large pitch, and the two mechanical joints which fix the two parts together are not shown. The darker ring represents a conductor carrying the electric current that the sensor is measuring. The inner windings of the inboard and outboard parts are connected in the bottom joint, and the ends of the outer windings constitute the terminals of the sensor. In the case of the CER however, for calibration purposes and for possible use of one half in case of failure of the other half, the two parts are considered as individual sensors. That is to say, instead of realising the electrical connection in the bottom joint, the two halves are put in series by switches in the data acquisition cards.

conducted in the paper.

### 3. Rogowski model in ideal geometry

For a general Rogowski coil, the flux linkage  $\varphi$  can be calculated in a simple way [4] by making the following two assumptions: i) the helical nature of the windings is not taken into account, that is the helices are approximated with sequences of independent turns lying in planes perpendicular to the path of the coil; ii) the magnetic flux density  $\mathbf{B}$  is considered spatially homogeneous over each cross-section. Hypothesis ii) is obviously satisfied since the coil's cross-section is small compared to field variations. By comparison with an integral code, we shall see now that i) is also verified.

If  $s$  is the arclength along the coil's path,  $N$  the total number of turns in each of the two windings,  $L$  the total length,  $\lambda = L/N$  the pitch length and  $n = 1/\lambda$  the turns density, so that the elemental number of turns is  $dN = nds$ , the flux is

$$\begin{aligned}\varphi &\cong \int_{\gamma} nds \int_S \mathbf{B} \cdot \hat{\mathbf{t}} dS \cong nS \int_{\gamma} \mathbf{B} \cdot \hat{\mathbf{t}} ds \\ &= \mu_0 S n \left( \oint_{\gamma^o} \mathbf{H} \cdot \hat{\mathbf{t}} ds - \int_{\gamma_j} \mathbf{H} \cdot \hat{\mathbf{t}} ds \right) \\ &= M_0 I - M_0 \lambda (H_{tl} N_l + H_{tu} N_u)\end{aligned}\quad (2)$$

where

$$M_0 = \mu_0 S n \quad (3)$$

is the nominal mutual inductance,  $\gamma = \gamma_i \cup \gamma_o$  the path along the inboard and outboard CER cables,  $\gamma_j = \gamma_u \cup \gamma_l$

the two segments corresponding to the upper and lower joints,  $\gamma^o = \gamma \cup \gamma_j$  the full closed path,  $\mathbf{H}$  the magnetic field,  $\hat{\mathbf{t}}$  the unit vector tangent to the path,  $I$  the threading current to be measured,  $N_u$  and  $N_l$  the 'missing' number of turns due to the presence of the joints,  $H_{tu}$  and  $H_{tl}$  the field tangent to the path at the joints. In short, the model in ideal geometry provides, for a threading current  $I$ , the mutual inductance as

$$M = \frac{\varphi}{I} = \mu_0 S n + \text{joints effect correction} \quad (4)$$

where, as reported in Tab. 1,  $S$  is the area corresponding to each single turn (including inner and outer winding turns).

Notice that the values  $H_{tl}$  and  $H_{tu}$  are due to all the field sources, including the threading current  $I$  itself. This is especially relevant in industrial applications, where Rogowski coils with circular shape are quite common, in both variants with single and double layer winding. For them, which typically have only one joint, it is

$$n = \frac{N}{2\pi r - \Delta L} = \frac{N}{(2\pi - \Delta\theta)r}$$

where  $r$  is the major radius of the Rogowski and  $\Delta L$  and  $\Delta\theta$  are, respectively, the arc length and angle corresponding to the gap due to the 'missing' turns in the joint region. When a circular Rogowski measures a straight current perpendicular to it and located at its centre, the flux is the same for all turns, hence the flux is  $N$  times the flux on each turn, and (2) reads as

$$\varphi \cong NS \frac{\mu_0 I}{2\pi r} - M_0 H_{tj}^e \lambda N_j$$

where  $N_{tj}$  and  $H_{tj}^e$  are the missing number of turns and the field tangent to the path due to external sources in the joint region. By external we mean all the field sources excluding the current  $I$  which is directly threading the coil. Notice again that the conductor which carries the current  $I$  has a return path which is external to the coil, and which gives a contribution to  $H_{tj}^e$ . This fact is for instance relevant for the calibration of the coil. When the threading current is not in the centre of the circular Rogowski, if the gap due to the joint is not small or compensated (see below), the correction term in (2) can be significant, specifically when the threading current is close to the joint.

When there aren't threading currents, in (2) it is  $I = 0$ , and  $\varphi$  is due to the joints effects correction only.

The CER diagnostic consists of the Rogowski loop, the transmission line and the data acquisition card. Since the latter has high input impedance, the acquired voltage signal  $v$  is proportional to the rate of change of the flux linkage with the windings,  $v = \frac{d\varphi}{dt}$ . Time integration and appropriate scaling of  $v$  provides the output signal  $\mathcal{I}$  of the diagnostic which, in the present case of ideal geometry, has then the very simple expression

$$\begin{aligned}\mathcal{I} &= \frac{\varphi}{M_0} = \int_{\gamma} \mathbf{H} \cdot \hat{\mathbf{t}} ds = \oint_{\gamma^o} \mathbf{H} \cdot \hat{\mathbf{t}} ds - \int_{\gamma_j} \mathbf{H} \cdot \hat{\mathbf{t}} ds \\ &= I - \lambda (N_l H_{tl} + N_u H_{tu})\end{aligned}\quad (5)$$

		Inner winding	Outer winding	Both windings
Winding diameters	[mm]	$2a = 5.5$	$2b = 8.3$	
Pitch length on axis	[mm]		$\lambda = 1$	
Wire diameter	[mm]		0.55	
Path (axis *) length	[m]		$L_0 = 38.6344^*$	
Ideal * # of turns			$N_0 = \frac{L_0}{\lambda} = 38634.4^*$	
Missing turns at joints			$N_i, N_u \leq 10$	
Total joints length	[mm]		$\Delta L \leq 20$	
Length	[m]		$L = L_0 - \Delta L \geq 38.6144$	
# of turns		$N = \frac{L}{\lambda} = N_0 - N_i - N_u \geq 38614.4$		$2N \geq 77228.8$
Turn density	[m <sup>-1</sup> ]	$n = \frac{N_0}{L_0} = \frac{N}{L} = \frac{1}{\lambda} = 1000$		$2n = 2000$
Ideal * equivalent area	[m <sup>2</sup> ]	$N_0 S_a = 0.918^*$	$N_0 S_b = 2.090^*$	$N_0 S = 3.008^*$
Equivalent area	[m <sup>2</sup> ]	$N S_a = 0.917$	$N S_b = 2.089$	$N S \geq 3.007$
Wire lengths	[m]	$L_{wa} \cong 668$	$L_{wb} \cong 1008$	$L_w \cong 1676$
Nominal sensitivity	[ $\mu\text{H} = \frac{\text{Vs}}{\text{MA}}$ ]	$M_{0a} = \mu_0 S_a n$	$M_{0b} = \mu_0 S_b n$	$M_0 = \mu_0 S n = 0.09784\ 7258$
Nominal gain factor	[ $\frac{1}{\mu\text{H}} = \frac{\text{MA}}{\text{Vs}}$ ]			$\frac{1}{M_0} = 10.22\ 0010$

\* For an ideal continuous coil without joints;  $S_a = \pi a^2$ ,  $S_b = \pi b^2$ ,  $S = S_a + S_b$

Table 1: Main design parameters of the CER sensor. For illustrative purposes, certain numerical values are artificially shown with a larger number of digits with respect to consistency to the required tolerance.

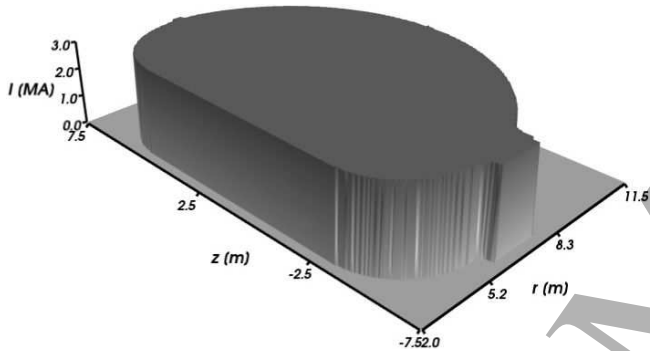


Figure 3: Functional testing of the integral code: calculated CER output due to a  $I = 3$  MA threading/non-threading current located at  $r$  &  $z$  variable over a 60000 points grid. The effect of the joints is not considered.

We shall see that, in the case of the CER sensor and in ideal geometry, the last equation can be stated as  $\mathcal{I} \cong I$  with excellent approximation. However, for general Rogowski coils, the contribution due to the presence of the joints can be significant. Whenever needed, it is possible to compensate their effect by winding a number of additional turns in the proximity of the gaps (e.g. inside the connectors) which subtract local fluxes corresponding to the areas  $SN_i$  and  $SN_u$ .

In order to take into account the unavoidable perturbations from ideal geometry of the windings, we will generalize Eq. (5). We will then refer to (5) as the *standard or canonical* Rogowski model.

#### 4. Validation of the model in ideal geometry

The model of the CER we will be using for all the analyses performs, in ideal geometry, the (discretised) line integral (5) of the magnetic field  $\mathbf{H}$  along the CER path,

excluding the joints. This is an approximation, since the CER in reality is a double helix rather than a set of circular turns. In order to estimate the accuracy of this simplified model, we used a general integral code [7], which was configured with the double winding helix defining the CER. The integral code is less versatile and computationally more expensive than the canonical model (5), and it is used only in this section to validate the latter. That is to say, with the aid of the integral code we are able to show that formula (5) calculates the flux linkage with very high accuracy.

Figure 3 visualizes the result of a basic functionality test of the integral code, showing the calculated output of the diagnostic  $\varphi/M_0$ , due to a  $I = 3$  MA threading/non-threading current located at  $r$  &  $z$  variable over a 60000 points grid, in the case of absence of joints. As numerical examples, we report in Tab. 2 the flux linkage of the CER for a filamentary current  $I = 15$  MA located in the centre (the average of the points of the target separatrix, see Fig. 4) and for various combination of joints. The outputs calculated with both the integral code and with (5) are shown. The agreement between the models is better than 0.2 ppm (about 7 digits agreement) in all the considered cases. The CER sensitivity (mutual inductance) is also shown.

Besides the data reported in Tab. 2, extensive comparison tests were performed to assess the canonical model versus the integral code. In all cases the agreement between the two models is better than 1 ppm. Thus we conclude that the error due to the approximation of the flux linkage with a discrete sum of fluxes linked with circular turns is negligible. The simplified model is then used for all the analyses.

$N_u$	$N_l$	$N$	$N\pi(a^2 + b^2)$	$\varphi$ [Wb]	$\varphi_i$ [Wb]	$\frac{\varphi - \varphi_i}{\varphi_i}$	$M_i = \frac{\varphi_i}{I}$
		1 winding	[m <sup>2</sup> ]	Eq. (??)	integral code	relative difference	$[\frac{\mu\text{H}}{10^6} = \frac{\text{Vs}}{\text{MA}}]$
0	0	38634.4	3.0082	1.467 708 870	1.467 709 127	$-0.1751 \cdot 10^{-6}$	0.09784 727
0	20	38614.4	3.0067	1.467 423 075	1.467 423 332	$-0.1750 \cdot 10^{-6}$	0.09782 822
20	0	38614.4	3.0067	1.467 327 546	1.467 327 803	$-0.1753 \cdot 10^{-6}$	0.09782 185
<b>10</b>	<b>10</b>	38614.4	3.0067	1.467 375 310	1.467 375 567	$-0.1749 \cdot 10^{-6}$	0.09782 504
20	20	38594.4	3.0051	1.467 041 750	1.467 042 007	$-0.1752 \cdot 10^{-6}$	0.09780 280

Table 2: Flux for  $I = 15$  MA calculated with Eq. (5) and with a general integral code. A substantial 7 digits agreement appears. The presence of the joints affects the 5-th digit.

Coil	current $I$	joints lengths $L_j$ [mm]	calculated output $\mathcal{I}_{L_j}$ [MA]	$M_{L_j} = \frac{\varphi}{I} = \frac{M_0 L_j}{I}$ [ $\mu\text{H} = \frac{\text{Vs}}{\text{MA}}$ ]	$\mathcal{I}_{L_j} - \mathcal{I}_0$	$M_{L_j}/M_0 - 1$
					joints effect	
plasma *	15 MA	0	15.000 000	0.0978 473	—	—
		5+5	14.998 295	0.0978 361	-1.70 kA	$-0.114 \cdot 10^{-3}$
		10+10	14.996 591	0.0978 250	-3.41 kA	$-0.227 \cdot 10^{-3}$
VS3U †	+0.24 MA	0	+0.240 000	0.0978 473	—	—
		5+5	+0.239 908	0.0978 097	-92 A	$-0.383 \cdot 10^{-3}$
		10+10	+0.239 816	0.0977 722	-184 A	$-0.767 \cdot 10^{-3}$
VS3L †	-0.24 MA	0	-0.240 000	0.0978 473	—	—
		5+5	-0.239 961	0.0978 315	+39 A	$-0.161 \cdot 10^{-3}$
		10+10	-0.239 922	0.0978 157	+77 A	$-0.323 \cdot 10^{-3}$
Source vs source		$L_j$ [mm]	$M_{L_j}^{\text{plasma}}/M_{L_j}^{\text{VS3U}} - 1$	$M_{L_j}^{\text{plasma}}/M_{L_j}^{\text{VS3L}} - 1$	$M_{L_j}^{\text{VS3U}}/M_{L_j}^{\text{VS3L}} - 1$	
sensitivity		0	0	0	0	
difference		5+5	$+0.270 \cdot 10^{-3}$	$+0.048 \cdot 10^{-3}$	$-0.222 \cdot 10^{-3}$	
		10+10	$+0.540 \cdot 10^{-3}$	$+0.096 \cdot 10^{-3}$	$-0.444 \cdot 10^{-3}$	

\* Implemented as a single filament located at  $r = 6.054$  m,  $z = 0.474$  m (average of target separatrix points)

† Implemented as a single filament; total maximum current in a pulse (4 turns), with pulse duration less than about 0.3 s [13, 16]

Table 3: Output of the ideal CER, in terms of measured current, due to a filament located in the centre and at the VS3 coils. The sensitivity and the coil to coil sensitivity differences are also shown, as well as the effect of the joints in absolute and relative terms.

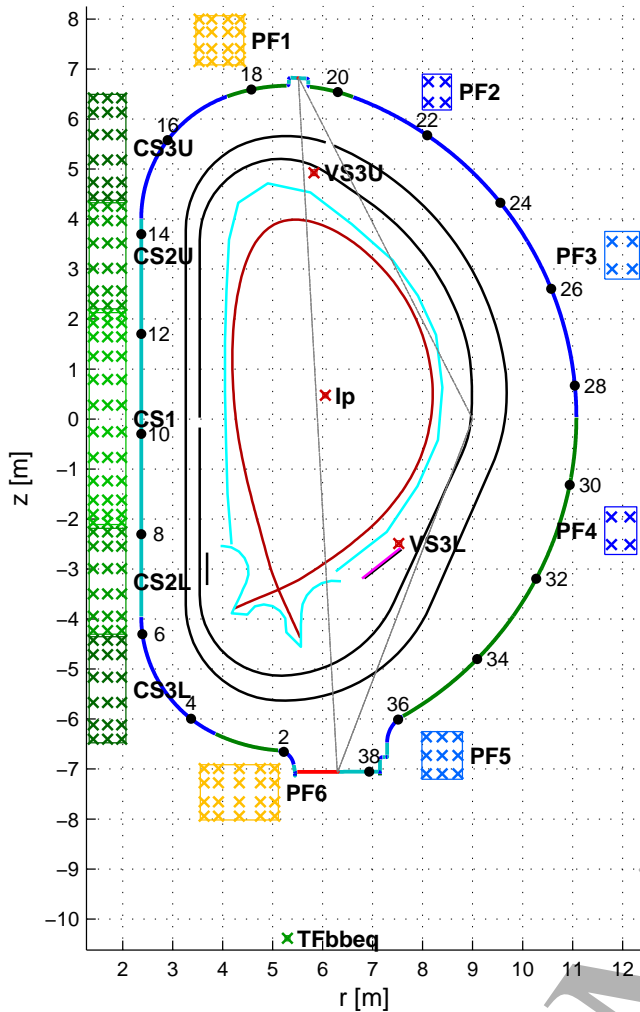


Figure 4: ITER poloidal section, showing the non-threading sources (the CS and PF coils and the equivalent axisymmetric model of the TF busbars), the CER (quoted with the arc-length starting at the lower joint), the vessel, the internal VS3 coils, the first wall and the target separatrix. The crosses denote the gauss integration points [14, pag. 85] used to calculate the field due to the each source. Their configuration is optimal, that is an increase of their number would not increase accuracy. The piecewise straight gray lines ending at the joints are an example of equivalent integration path (see § 13). TFbreq stands for the TF busbars, implemented as their equivalent axisymmetric model [13, 16].

## 5. Effect of the joints in ideal geometry

The most relevant joints combinations are the following:

- no joints (ideal continuous Rogowski coil)
- 10+10 mm joints (worst case as from CER specifications)
- 5+5 mm joints (about best achievable with reference joints connector design [13, 15]).

### 5.1. Threading coils

In the worst case specification of 10+10 mm joints, the joints/CER length ratio is  $L_j/L \sim 0.5 \cdot 10^{-3}$ . Hence we expect a joint effect of such order of magnitude for threading

currents. However, a role is also played by the fact that the CER has an elongated shape (Fig. 4), so that different current configurations imply different effects. Table 3 considers a filamentary current located at three different threading locations, namely the centre (the average of the points of the target separatrix) and the positions occupied by the VS3 coils [13, 16]. The CER output is now expressed in terms of measured current (Eq. (5)) rather than as flux linkage. We see that indeed the effect of the joints depends on the relative location of the current versus the joints. It is in particular stronger in the case of VS3U, which is comparatively closer to the (upper) joint. The lower part of the table expresses that, in the worst spec case (10+10 mm joints) the source to source sensitivity differences are about: 550 ppm for  $I_p$  vs  $I_{VS3U}$ , 100 ppm for  $I_p$  vs  $I_{VS3L}$ , 450 ppm for  $I_{VS3U}$  vs  $I_{VS3L}$ . The effect is halved in the case of 5+5 mm joints. The fact that the difference is smaller in the case  $I_p$  vs VS3L is somewhat witnessed in Fig. 5 too, which represents, as functions of the poloidal location, the elemental contributions to the CER signal in ideal geometry due to all the sources shown in Fig. 4, at their maximum admissible current values [13, 16]. Fig. 5 also shows the sum of the contribution of all the external sources. The gray plots give the magnitude of the local magnetic field, whereas the black ones are the aliquot which contribute to the CER signal.

As remarked in § 3, it would be possible to compensate the joints effect. For the CER this is not needed for the following reasons (see also § 5.2 below):

- the impact on the threading currents is less than an order of magnitude below measurement tolerance specification;
- the actual joints lengths and their effect can be characterized and compensated (see § 10);
- unavoidable deviation from the ideal geometry of the CER have a larger impact on the threading currents, as we shall see.

### 5.2. Cross-talk of the non-threading coils

Table 4 reports the cross talk of the non-threading coils with the ideal CER, in terms of measured current and sensitivity, in the worst case condition for the joints (10+10 mm). The details of the coils are described in [13, 16]. CS1U and CS1L are considered separately in Tab. 4 for illustrative purpose but, everywhere else in the paper, they are treated as a single source, for they are actually connected in series (Fig. 4–5 also consider a single CS1 coil). As seen in § 3, the output due to non-threading currents in ideal geometry only depends upon the field at the joints locations and on the joints characteristics themselves. Hence the cross talk is due to the presence of the joints (in ideal geometry), and the values shown in Tab. 4 get halved in the case of 5+5 mm joints. We see that the TF busbars, implemented as their equivalent axisymmetric model [13, 16], have a tiny effect (15 A), whereas the coils giving the largest contribute ( $\sim 3$  kA) are PF1 and

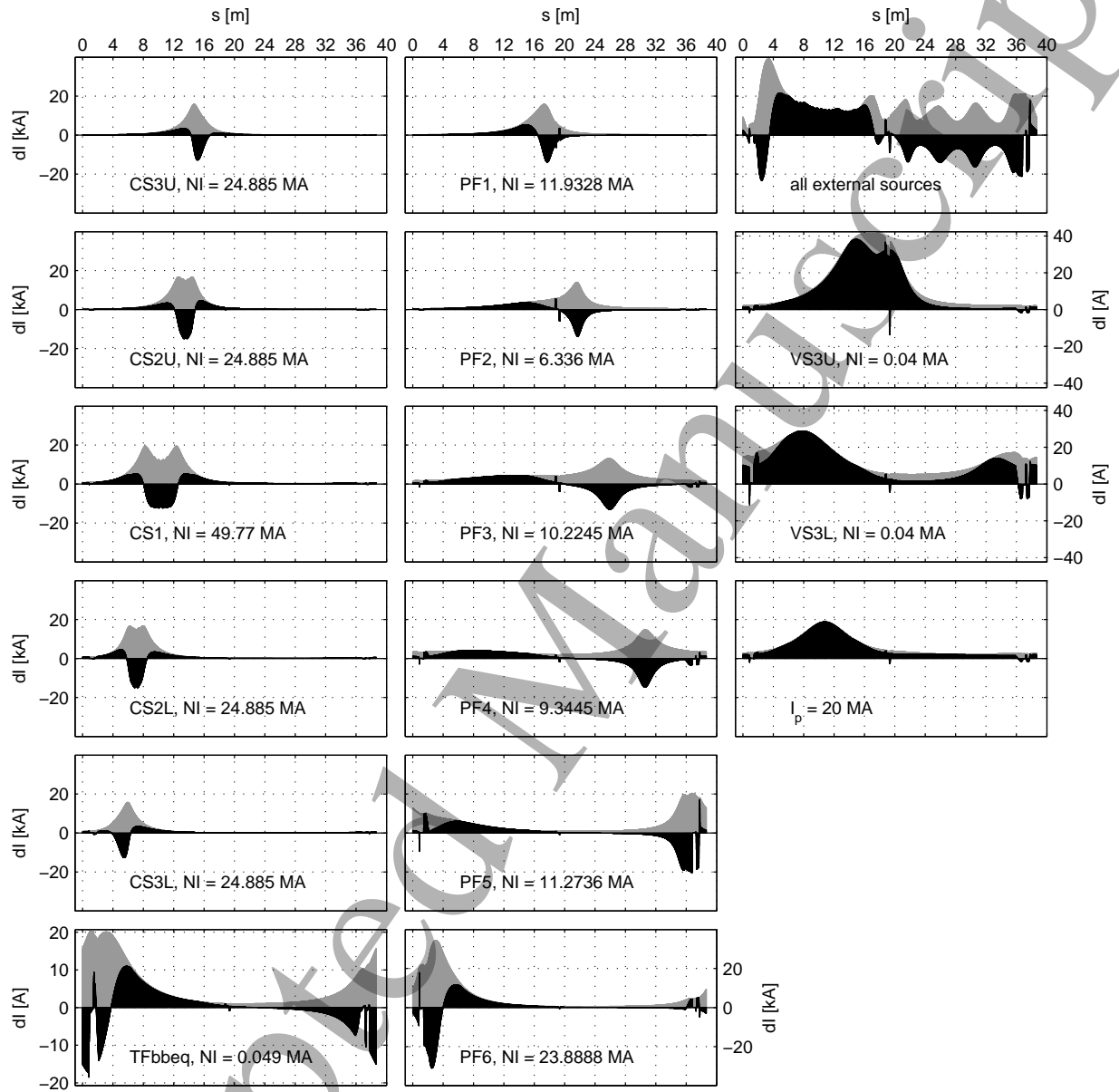


Figure 5: Patterns representing, as functions of the poloidal location, the elemental contributions to the CER signal in ideal geometry due to all the sources shown in Fig.4, at their maximum nominal current values [13, 16]. The top-right one refer to the sum of the contribution of all the external sources. The bar graphs in gray and black color represent the magnitude of the local field  $|\mathbf{H}|\Delta s$  and the aliquot which contribute to the CER signal in ideal geometry  $\Delta I = \mathbf{H} \cdot \hat{\mathbf{t}}\Delta s$ , respectively. TFbreq stands for the TF busbars, implemented as their equivalent axisymmetric model [13, 16].



Coil	$N$ (turns)	$I_{\max}$ [kA]	$NI_{\max}$ [MA $\cdot$ T]	$\mathcal{I}$ [kA]	$M = \frac{\varphi}{NI_{\max}}$ [pH]
CS3U	553	45	24.885	-0.87	-3.42
CS2U	553	45	24.885	-1.03	-4.06
CS1U	553	45	24.885	-0.76	-2.99
CS1L	553	45	24.885	-0.68	-2.67
CS2L	553	45	24.885	-0.75	-2.95
CS3L	553	45	24.885	-0.58	-2.28
PF1	248.6	48	11.933	+3.19	+26.2
PF2	115.2	55	6.336	-0.30	-4.65
PF3	185.9	55	10.225	-1.45	-13.9
PF4	169.9	55	9.345	-1.71	-17.9
PF5	216.8	52	11.274	-1.66	-14.4
PF6	459.4	52	23.889	+2.71	+11.1
TFbbeq	1	49	0.049	+0.015	+29.2

Table 4: CER output in ideal geometry due to the external axisymmetric coils at their maximum nominal currents [13, 16], in the worst case condition for the joints (10+10 mm). The shown values get halved in the case of 5+5 mm joints. TFbbeq stands for the TF busbars, implemented as their equivalent axisymmetric model [13, 16].

PF6, which are the closest to the upper and lower joint, respectively. The exact location of the lower joint was not precisely specified at the time the analyses have been performed. We placed it in the centre of the corresponding straight path. For this reason, the calculated outputs corresponding to PF5 & PF6 can be less precise due to possible (minor) differences with respect to the location here considered. This is however not really important. In fact, to the points a,b,c stated in § 5.1 above, we can add the following:

- d. the cross talk of the non-threading coils in ideal geometry can be compensated;
- e. the deviation from the ideal geometry of the CER have a larger impact on the non-threading currents cross-talk as well (this effect can also be compensated, see § 10).

Then, the cross-talk in ideal geometry reported in Tab. 4, have to be considered mainly as reference information, and not as measurement errors.

## 6. Measurement error: analysis of the deviation from ideal geometry of Rogowski windings

The manufactured sensor will not be geometrically ideal. In particular, the need of having sufficiently uniformly wound coils was accounted for since the days of the early experimentalists. Citing Chattock (1887) [1]: “*The use of the lathe is the more desirable, as measurements of potential by the helix depend very much for their accuracy upon the uniformity with which it is wound; this being especially the case if its position in the field does not happen to coincide with the direction of the lines of force.*” Analogue statements are found in the current literature [5]. The issue is intuitively clear by imagining e.g. extreme cases of

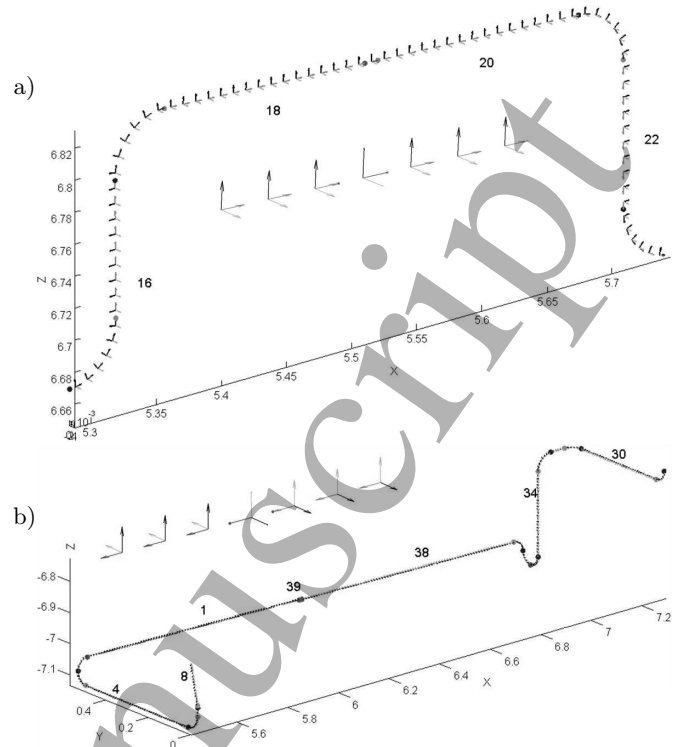


Figure 6: Reference frames defined at the integration points in the upper (a) and lower (b) joint regions (not to scale, cfr. Fig. 1, 4). The numeric labels indicate a selection of the 39 segments with which the various parts of the CER path (inboard/outboard CER and joints) are defined. The magnified insets show the frames across the joints.

winding non-uniformity. Up to our knowledge, quantitative methods are not available. To formulate the problem, we model the deviations from ideal geometry by considering the following effects:

- i) the variability of the pitch length  $\lambda$ , or equivalently of the turns density  $n = 1/\lambda$ ;
- ii) the variability of the area of the local turns,  $S = \pi(a^2 + b^2)$  (including both inner and outer winding turns);
- iii) the turns tilting, described by the colatitude  $\theta$  and the azimuth  $\phi$ ;
- iv) the (non-)centricity effect, due to the fact that the axes of the inner and outer windings will not be exactly coincident; relevant parameters are the local distance between the axes  $\delta$  and the normal direction to the elemental area locally defined by the two axes, expressed as another independent azimuth  $\psi$ .

All the parameters are functions of the arc length  $s$  along the Rogowski path. Then, hereafter, we denote with a ring accent their values corresponding to ideal geometry, e.g.,  $\dot{n} = 1/\dot{\lambda}$  and  $\dot{M}_0 = \mu_0 \dot{S} \dot{n}$  are the unperturbed turns density and the ideal sensitivity.

In order to analyze the tilting and the centricity effects, it is needed to define a continuously varying reference frame along the Rogowski path, the trihedral

$\{\hat{\mathbf{t}}(s), \hat{\mathbf{n}}(s), \hat{\mathbf{b}}(s)\}$  [17], with respect to which the angle parameters  $\theta(s), \phi(s), \psi(s)$  are specified.

The path of the CER is defined as a 3-D sequence of straight and circular segments, which we divided into two main sets, corresponding to the inboard and outboard CER cables, plus two more small segments, representing the joints. Specifically (see also Fig. 6):

- segments 1-18: inboard CER;
- segment 19: upper joint, with a nominal 10 mm length (worst case);
- segments 20-38: outboard CER;
- segment 39: lower joint, with a nominal 10 mm length (worst case).

The clearer separation between the inboard and outboard parts of the device allows to consider the two halves as independent sensors, which can be useful in particular for the calibration (§ 13) or in case of failure of one half.

The discretized reference we implemented considers 3863 integration points, so that the average step in terms of arc length is  $\langle \Delta s \rangle = 1$  cm, with a minimum  $\Delta s_{\min} = 7.9$  mm on segment 7. Figure 6 shows the corresponding sequences of trihedrals in the upper and lower joint regions, where the routing is more complex. The unit vectors  $\hat{\mathbf{t}}, \hat{\mathbf{n}}$  are respectively tangent and normal to the path, while the binormal  $\hat{\mathbf{b}}$  is given by  $\hat{\mathbf{b}} = \hat{\mathbf{t}} \times \hat{\mathbf{n}}$ . Specifically, on the larger arc segments of the path, we define  $\hat{\mathbf{n}}$  as having the same direction of  $-\frac{d\hat{\mathbf{t}}}{ds}$  (the opposite of the curvature vector), so that it lies in the poloidal plane and it is outward directed. On the straight segments and on certain arcs in the feed-out region, we instead define  $\hat{\mathbf{n}}$  so that the trihedral is a continuous function of  $s$ . This continuity property is preserved along the whole inboard and outboard CER paths and while crossing the upper joint as well (Fig. 6a), but not across the lower joint (Fig. 6b). The latter is mentioned only for completeness and to state that it doesn't have any implication. Notice that, since the path is defined as a 3-D sequence of segments, the trihedral could not be analytically determined as the Frenet frame [17], as it would be discontinuous at the knots of the CER path and undefined on the straight segments.

Effects i) and ii) act in the same way, thus we define a local gain parameter

$$\kappa = \frac{S_n}{\dot{S}_n}.$$

The turns tilting is analysed with the aid of the unit vectors

$$\hat{\boldsymbol{\tau}} = \cos \theta \hat{\mathbf{t}} + \sin \theta \hat{\boldsymbol{\rho}}, \quad \hat{\boldsymbol{\rho}} = \cos \phi \hat{\mathbf{n}} + \sin \phi \hat{\mathbf{b}},$$

$\hat{\boldsymbol{\tau}}$  being a perturbed version of  $\hat{\mathbf{t}}$ , normal to the turns of the winding. The centricity effect is then formalised by means of a centricity factor  $\varepsilon$  and a unit vector  $\hat{\boldsymbol{\rho}}$  (normal to the elemental area spanned by the displacement  $\delta$  between the geometrical axes of the two windings) defined as

$$\varepsilon = \frac{\delta}{\dot{S}_n}, \quad \hat{\boldsymbol{\rho}} = \cos \psi \hat{\mathbf{n}} + \sin \psi \hat{\mathbf{b}}.$$

Given a specific geometric pattern defined by the five quantities  $\kappa, \theta, \phi, \delta, \psi$ , which are functions of  $s$ , the CER output is then expressed as follows

$$\mathcal{I} = \frac{\varphi}{M_0} = \frac{\int_{\gamma} n S \mathbf{B} \cdot \hat{\boldsymbol{\tau}} ds + \int_{\gamma} \delta \mathbf{B} \cdot \hat{\boldsymbol{\rho}} ds}{\dot{S}_n \mu_0} = \int_{\gamma} \mathbf{H} \cdot \mathbf{T} ds \quad (6)$$

where

$$\mathbf{T}(s) = \mathbf{T}(\kappa, \theta, \phi, \delta, \psi) = \kappa \hat{\boldsymbol{\tau}}(\theta, \phi) + \varepsilon(\delta) \hat{\boldsymbol{\rho}}(\psi). \quad (7)$$

Eq. (6) generalises the classical expression (5) and allows to compute the effects due to the nonideal geometry of the winding.

The turns tilting and centricity effects are somewhat similar, since they both cause pickup of perpendicular flux. In the case of the CER, the values of the involved parameters (see next section) imply that the error due to the centricity effect always is a small fraction of the tilting one (§ 9).

## 7. Measurement error: statistical model

The measurement error is evaluated in statistical fashion in terms of twice its standard deviation [10, 13]. The error will then be denoted as  $2\sigma$ . To determine it, we consider:

- $N_{cp}$  total control points along the routing: 4 of them are fixed (the initial and final ends of the two half CER cables), while the remaining ones are randomly located, with uniform distribution, along the inboard and outboard CER paths ( $N_{cp}/2 - 2$  for each half CER);
- $f_s$  = spatial frequency of the geometric deviations =  $1/\langle \Delta s \rangle = 1/(\text{average spacing among control points})$ ;
- all the geometric deviation parameters are randomly generated at each control point, and then interpolated at each integration point (a  $C^1$  interpolation scheme is applied in order to avoid overshoots).

We take the local gain parameter,  $\kappa$ , as normally distributed with mean 1 and a standard deviation,  $\sigma_{\kappa}$ , to be specified. The turns tilting colatitude,  $\theta$ , and the centricity displacement,  $\delta$ , are also given normal distributions, but with mean 0, and certain standard deviations,  $\sigma_{\theta}$  and  $\sigma_{\delta}$ . The azimuth tilting and centricity parameters,  $\phi$  and  $\psi$ , need instead to be uniformly distributed in the interval  $[-90, 90]$  deg. That spans the 4 quadrants, since  $\theta$  and  $\delta$  take positive and negative values. To determine  $\sigma_{\kappa}$ ,  $\sigma_{\theta}$  and  $\sigma_{\delta}$ , we consider that, for a normal random variable with standard deviation  $\sigma$ , the interval  $[-3\sigma, +3\sigma]$  corresponds to 0.9973 probability, essentially 100 % of the whole distribution. For the local gain, measurements were made on prototypes [18], which suggest to take 2 % as maximum deviation. From the CER cable specifications, we then take 0.5 mm as maximum centricity displacement. And, since there aren't information about realistic maximum deviation of the tilting colatitude angle, we need to leave

it as a parameter. The maximum geometric deviations are also used to calculate the theoretical worst case errors. In summary, the quantities of the statistical model which we consider known are (wc stands for worst case):

$$\begin{aligned} |\pm \Delta\kappa_{wc}| &= \Delta\kappa_{\max} = 3\sigma_{\kappa} = 0.02 \\ |\pm \delta_{wc}| &= \delta_{\max} = 3\sigma_{\delta} = 0.5 \text{ mm} \\ |\pm \phi_{\max}| &= |\pm \psi_{\max}| = 90 \text{ deg} \end{aligned}$$

whereas the quantities that we leave as parameters are  $f_s$  and  $\sigma_{\theta}$ . Specifically, the statistical error is mainly calculated on the following grid of values:

$$\begin{aligned} f_s &= \frac{1}{\langle \Delta s \rangle} = \{0.2, 2, 5, 20\} \text{ m}^{-1} \text{ (control points per meter),} \\ |\pm \theta_{wc}| &= \theta_{\max} = 3\sigma_{\theta} = \{1, 2, 4, 8\} \text{ deg.} \end{aligned}$$

We speculate that  $\theta_{\max} = 8 \text{ deg}$  is an extreme and unrealistic condition, and consider  $f_s = 0.2 \text{ control points per meter}$  as the limiting and unlikely condition for the spatial frequency parameter, since it implies local systematic geometric deviations.

## 8. Measurement error: worst case analysis

Besides the statistical error, it is interesting to evaluate the worst case theoretical error(s). Their determination is performed by considering a *minimization geometrical pattern* and a *maximization geometrical pattern*, for which the CER output is respectively minimized and maximized. The analysis is specific for each of the three effects considered.

The minimum output  $\mathcal{I}_{\min}$  due to non-ideal local gain is obtained by applying a 2% reduction to all the elemental contributions (single turn fluxes) which are positive, and a 2% increase where they are negative. Vice versa for the maximum output  $\mathcal{I}_{\max}$ . It turns out that the error (the difference between the min/max output and the output in ideal geometry  $\hat{\mathcal{I}}$ ) is the same in absolute value for the min and max cases.

For the tilting effect, the maximum (minimum) output is obtained when the normal to each turn is rotated as much as possible towards (away from) the direction of the local magnetic field. In this case the error isn't the same in absolute value for the min and max cases.

The centricity effect, like the tilting, imply a pickup of the flux perpendicular to the path of the CER. The maximizing procedure consists of evaluating, at each integration point, the elemental flux through the area  $\lambda\delta_{\max}$  due to the projection of the field in the plane determined by the normal and binormal directions. Unlike the tilting, and like the local gain, the centricity error is the same in absolute value for the min and max cases.

## 9. Computation of the measurement error: effect of the ferromagnetic inserts

In the present and in subsequent sections we apply the

proposed methods to compute numerically the measurement errors. We do that for the CER sensor with the aid of a number of suitable operating reference scenario. These constitute a very small subset of case, which obviously are not intended to be representative as a catalogue of the most important reference scenarios of the ITER machine, and which are fully sufficient to evaluate the performances of the CER diagnostic. This will be clear from the outcome of all the analyses we will perform. We anticipate the main reasons, which are the following. Firstly, recall that (see § 1) the ITER design description documents [9, 10] specify that the CER is not intended to be used during transients. Its function is to measure  $I_p$  in steady-state condition. This is due to the shielding of the Vacuum Vessel (VV). We will assess the measurement error in two different flat-top configurations and will see that the measurement error is the same. This result is due to a more general property. In fact, it is a known experimental evidence that Rogowski loops are quite effective current sensors, meaning that they provide a reliable and accurate measure of the total current threading the loop itself and are essentially insensitive to the current density distribution and to its time variation properties (for variations within the sensor's bandwidth, which is clearly the case, due to the large time constant of the VV shielding (Fig. 9)). Our methods consent to confirm this evidence in quantitative terms and provide a precise and complete performance assessment. In particular we will show that the computed measurement error is essentially the same in all considered cases and does not change for different plasma and eddy current configurations (see e.g. Fig. 14).

In this section we evaluate the measurement errors in ideal and non-ideal geometric configuration of the CER, for a flat-top configuration with plasma current  $I_p = 15 \text{ MA}$ . The input data, represented by the total field  $\mathbf{H}(\mathbf{r})$ , were obtained with a 3-D numerical model [19–21], which implements an iterative procedure based on an integral formulation and includes the ferromagnetic inserts (FI) of ITER [12]. In order to indicate all the considered contributions, the error in non-ideal geometry will be denoted as  $2\sigma(\mathcal{I}_p + \mathcal{I}_{\text{coils}} + \mathcal{I}_{\text{FI}})$ , and in similar way in subsequent sections.

### 9.1. Ideal CER geometry

In the ideal case of unperturbed geometry of the CER windings, in the output signal there will be a contribution of the FI due to the presence of the joints. The CER is an inductive sensor whose output voltage  $v$  is the time derivative of the flux linkage. The measured current is obtained by scaling and time-integrating the voltage  $v$ . Since the toroidal field current has the same value before and during pulses, and the integrator is reset at the beginning of the pulse, the actual measured output is given by

$$\Delta\mathcal{I} = \mathcal{I}_1 - \mathcal{I}_0 = \frac{\varphi_1 - \varphi_0}{M_0} = \frac{1}{M_0} \int_{t_0}^{t_1} v(t) dt$$

Flat-top, $I_p = 15$ MA				
Contributions: plasma+CS+PF+FI (TF subtracted due to integration)				
Total statistical error (5000 runs) due to all geometric deviations ( $\Delta\kappa_{\max} = 0.02$ , $\delta_{\max} = 0.5$ mm, $\theta_{\max}$ parameter)				
$\theta_{\max} = 3\sigma_\theta$	$\frac{100 \cdot 2\sigma(\mathcal{I}_p + \mathcal{I}_{\text{coils}} + \mathcal{I}_{\text{FI}})}{I_p}$ [%]			
$1^\circ$	<i>0.94</i>	0.45	0.29	0.15
$2^\circ$	<i>1.09</i>	0.55	0.36	0.19
$4^\circ$	<i>1.54</i>	0.83	0.57	0.29
$8^\circ$	<i>2.68</i>	<i>1.51</i>	<i>1.04</i>	<i>0.54</i>
$\approx f_s = \frac{1}{(\Delta s)} [\text{m}^{-1}]$	<i>0.2</i>	2	5	20
$N_{\text{CP}}$	<i>10</i>	76	190	760

Table 5: Calculated measurement error  $2\sigma$  in the case of flat-top plasma configuration and in presence of the ferromagnetic inserts, parametrised versus the spatial frequency of the geometrical deviations  $f_s$  and the maximum tilting angle  $\theta_{\max}$ . The values in italic font correspond to the limiting region of the parameters that we consider unrealistic. Just for completeness, we report that the calculation was performed with the worst case joint configuration (10+10 mm).

where  $\mathcal{I}_1$  and  $\mathcal{I}_0$  are the calculated outputs respectively at flat-top and before the start of the pulse. This is possibly relevant because the FI provide a contribution off pulse as well. We specifically get, in ideal geometry and with 10+10 mm joints:  $\mathcal{I}_{m0} = 0.012$  A (pre-pulse contribution to the calculated CER output due to the magnetization);  $\mathcal{I}_{m1} = -11.8$  A (contribution to the calculated CER output at flat-top due to the magnetization). Thus the aliquot in the output due to the FI is  $\Delta\mathcal{I}_m = \mathcal{I}_{m1} - \mathcal{I}_{m0} = -11.8$  A. For the typical plasma current  $I_p = 15$  A, we get  $\Delta\mathcal{I}_m/I_p = -0.79 \cdot 10^{-6}$ . The effect of the ferromagnetic insert in ideal geometry is then less than 1 ppm (halved for 5+5 mm joints), hence it is negligible.

### 9.2. Perturbed CER geometry

Table 5 shows the total measurement error  $2\sigma(\mathcal{I}_p + \mathcal{I}_{\text{coils}} + \mathcal{I}_{\text{FI}})$ , calculated with the statistical model described in § 7, and parametrised versus the spatial frequency of the geometrical deviations  $f_s$  and the maximum tilting angle  $\theta_{\max}$ . All the geometric effects are considered and act simultaneously and independently. As expected, the error decreases with  $f_s$ . We can see that, apart from the results corresponding to limit/unrealistic values of the parameters (in italic font), the error due to the non-ideal geometry of the CER is below 1%. We will show that this error can significantly be reduced, for the contribution of the CS and PF coils can be compensated.

Table 6 provides more details in the specific case where the maximum tilting angle is  $\theta_{\max} = 2$  deg. The worst case and the statistical errors are reported, when each geometric effect acts individually as well. Unlike the global view of Tab. 5, which takes all the sources into account (plasma+CS+PF+FI) at once, here the ferromagnetic inserts are separately analyzed, leading to the conclusion

that their effect to the measurement error is negligible in non-ideal CER geometry too.

Since the FI are saturated by the toroidal field, for them the equivalent linear permeability model in the poloidal direction [22, 23] holds. Thus the FI contribution to the measurement can be evaluated by such model. That implies that the FI contribution approximately scales with  $I_p$ . Hence, the error due to the FI is negligible in the case of pulses with lower plasma current as well.

Table 6 also let us appreciate that the error due to the centricity effect is small (even smaller after CS&PF compensation, see next section). Indeed, as anticipated in § 6, the values of the involved parameters imply that the centricity error is a fraction of the error due to turns tilting. Specifically, it is about 1/6 of the error due to a maximum tilting  $\theta_{\max} = 3\sigma_\theta = 2$  deg. This is a general result, not limited to the case considered in the present section.

It is interesting to visualize the patterns corresponding to the minimum and maximum measurement error on the output of the CER signal in the considered statistical set, consisting of 5000 runs. In the example shown in Fig. 7 the local gain  $nS$  is randomly varying, while the other parameters are set to the values they have in ideal geometry. The first and second parts of each plot, respectively drawn in black and gray color, correspond to the inboard and outboard CER cables. The dots represent the  $N_{\text{CP}}$  control points. The plots in the first and second rows refer to the contribution of the source plasma+CS+PF, whereas the third and fourth rows consider the FI contribution. For the first, second and third column it is respectively  $N_{\text{CP}} = 10, 76, 760$ , namely  $f_s \approx 0.2, 2, 20$  control points per meter.

## 10. Computation of the measurement error during transients, poloidal field compensation and statistical error distribution

In this section we estimate the effect of the eddy currents on the measurement error. The performed computations show that, as anticipated in § 9 and as expected from a well engineered Rogowski coil, the CER performances don't depend on the characteristics of the threaded current distribution (see also the results reported in § 11). We then analyze how the measurement error improves significantly by compensating the contribution due to the poloidal field coils. The use of the first instants of the simulation allows to get such result for the flat top configuration as well. This result is also reflected into corresponding changes of the statistical error distribution.

The input data  $\mathbf{H}(\mathbf{r}, t)$  we consider correspond to the scenario MD UP PFV (Major Disruption Up, Poloidal Field Variation), and were obtained with a 3-D numerical model [19–21]. We chose this configuration because it is an important one, as it implies a very short ( $< 50$  ms) current quench [11], and because it consents to show in a clear way the shielding properties of the VV. Figure 8a) depicts the time-evolution of the main quantities (plasma

Contribution (@ flat top) of	Kind of geometric deviation	Worst case		Statistical analysis (5000 runs)												
		$\Delta\mathcal{I}_{\min}$ [kA]	$\Delta\mathcal{I}_{\max}$ [kA]	$f_s \approx \frac{1}{4.8\text{ m}} \approx 0.2\text{ m}^{-1}$ $N_{\text{cp}} = 10$			$f_s \approx \frac{1}{50\text{ cm}} = 2\text{ m}^{-1}$ $N_{\text{cp}} = 76$			$f_s \approx \frac{1}{5\text{ cm}} = 20\text{ m}^{-1}$ $N_{\text{cp}} = 760$						
				$\frac{100\Delta\mathcal{I}}{I_p}$ [%]	$\Delta\mathcal{I}_{\min}$ [kA]	$\Delta\mathcal{I}_{\max}$ [kA]	$2\sigma$ [kA]	$\frac{100\cdot 2\sigma}{I_p}$ [%]	$\Delta\mathcal{I}_{\min}$ [kA]	$\Delta\mathcal{I}_{\max}$ [kA]	$2\sigma$ [kA]	$\frac{100\cdot 2\sigma}{I_p}$ [%]	$\Delta\mathcal{I}_{\min}$ [kA]	$\Delta\mathcal{I}_{\max}$ [kA]	$2\sigma$ [kA]	$\frac{100\cdot 2\sigma}{I_p}$ [%]
Plasma 15 MA +CS+PF (TF subtracted due to integration)	<i>nS</i> tilting centricity all	$\pm 564$	$\pm 637$	3.8	-288	+286	131	<i>0.87</i>	-123	+125	62	0.41	-47	+39	20	0.13
FI @ $I_p = 15$ MA ( $\sim$ scale with $I_p$ )	<i>nS</i> tilting centricity all	-1.9	+1.9	0.013	-0.70	+0.66	0.37	<i>0.002</i>	-0.29	+0.27	0.14	0.001	-0.09	+0.07	0.04	0.0003
		$\pm 0.353$		0.0023	-0.17	+0.16	0.07	<i>0.0004</i>	-0.14	+0.14	0.03	0.0002	-0.03	+0.01	0.01	0.0001
					-0.93	+1.02	0.53	<i>0.003</i>	-0.49	+0.45	0.23	<b>0.002</b>	-0.15	+0.12	0.07	<b>0.0005</b>

Table 6: Detail of the calculated measurement error for the flat-top plasma configuration, and for the specific case where the maximum tilting angle is  $\theta_{\max} = 2$  deg, parametrised versus the spatial frequency of the geometrical deviations  $f_s$ . Reading code: italic font correspond to the limit region of the  $f_s$  parameter that we consider unrealistic; in bold are negligible errors due to the FI; boxed values represent errors that can significantly be reduced by means of poloidal field compensation (§ 10).

and halo currents, diamagnetic flux, position of the plasma current centroid). The numerical model (Fig. 8 b), which is made of 8519 elements and has 9848 discrete degrees of freedom, includes: vessel inner and outer shell; copper cladding; ribs; upper, equatorial, lower port extension; rail; cassettes; inner vertical targets; outer vertical targets; dome. The first two plots in Fig. 9 show the contribution of the relevant sources to the calculated CER output in ideal geometry, and a zoom in the range 0–100 ms. The eddy currents give the max contribution at  $t = 50$  ms. From  $t = 50$  ms onwards it is  $I_p = 0$ . Notice that, when  $I_p$  start decreasing, the eddys start to rise so that their sum, namely the CER output, remains approximately constant during the event. Hence the CER cannot be used as a direct measure of  $I_p$  in general conditions. More specifically, from the first plot in Fig. 9, one can estimate the toroidal time constant of the Vacuum Vessel (VV) as  $\tau_{\text{VV}} \approx 0.5$  s. Thus, during transient or fast events, the CER become aware of them about 0.5 s after they arise. As stated in the introduction, the CER is not intended to be used during transients for measuring  $I_p$ . The reference estimate of  $I_p$  for operation is provided by the in-vessel tangential coils [9]. In the last plot of Fig. 9 the calculated effect of the joints is shown: the eddys goes to zero asymptotically, whereas the presence of the joints themselves imply that the contribution due to the CS and PF coils, which are essentially constant throughout the scenario, remain present in the output.

Fig. 10 represents the contributions to the CER signal as functions of the poloidal location. The gray plots show the magnitude of the local magnetic field, whereas the black ones are the aliquot which contribute to the CER signal in the case of ideal geometry. The configuration considered is the one at  $t = 50$  ms, where the eddy currents provide the the maximum effect,  $\mathcal{I} \cong \mathcal{I}_{\text{eddy}} = 14.7$  MA, and it is  $I_p = 0$ .

In the case of the flat top configuration ( $t = 0$ ), for which  $\mathcal{I} \cong \mathcal{I}_p = 15$  MA, the patterns (not shown) are nearly identical to the one shown in Fig. 10. In both cases the

measured quantity (the total toroidal current) is about the same. In general, however, patterns are different (Fig. 14).

Configuration	MD UP PFV					
	Flat top $t = 0$ $I_p = 15$ MA $I_{\text{eddy}} = 0$			Max eddy $t = 0.05$ s $I_p \approx 0$ $I_{\text{eddy}} = 14.7$ MA		
Total statistical error (5000 runs) due to all geometric deviations ( $\Delta\kappa_{\max} = 0.02$ , $\delta_{\max} = 0.5$ mm, $\theta_{\max}$ parameter)						
Before CS & PF compensation						
	$\frac{100\cdot 2\sigma(\mathcal{I}_p + \mathcal{I}_{\text{coils}})}{\mathcal{I}_p + \mathcal{I}_{\text{coils}}}$ [%]		$\frac{100\cdot 2\sigma(\mathcal{I}_{\text{eddy}} + \mathcal{I}_{\text{coils}})}{\mathcal{I}_{\text{eddy}} + \mathcal{I}_{\text{coils}}}$ [%]			
2°	<i>1.23</i>	0.64	0.21	<i>1.25</i>	0.65	0.22
4°	<i>1.85</i>	1.00	0.34	<i>1.89</i>	1.02	0.35
8°	<i>3.51</i>	<i>1.83</i>	<i>0.63</i>	<i>3.39</i>	<i>1.87</i>	<i>0.64</i>
After CS & PF compensation						
	$\frac{100\cdot 2\sigma(\mathcal{I}_p)}{\mathcal{I}_p}$ [%]		$\frac{100\cdot 2\sigma(\mathcal{I}_{\text{eddy}})}{\mathcal{I}_{\text{eddy}}}$ [%]			
2°	<i>0.74</i>	0.29	0.09	<i>0.74</i>	0.29	0.09
4°	<i>0.79</i>	<b>0.33</b>	0.11	<i>0.79</i>	<b>0.33</b>	0.10
8°	<i>0.96</i>	<i>0.48</i>	<i>0.15</i>	<i>0.95</i>	<i>0.47</i>	<i>0.15</i>
$\theta_{\max} = 3\sigma\theta$	0.2	2	20	0.2	2	20
	$\approx f_s = \frac{1}{(\Delta s)} [\text{m}^{-1}]$					

Table 7: Calculated measurement error  $2\sigma(\cdot)$  for the MD UP PFV scenario, parametrised versus the spatial frequency of the geometrical deviations and the maximum tilting angle, before and after CS/PF compensation. The values in italic font correspond to the limit region of the parameters that we consider unrealistic, while the values in bold are a sensible upper bound estimate of the error due to the CER geometric imperfections. For completeness we report that the calculation were performed with the worst case joint configuration (10+10 mm).

Fig. 10(a) includes the cross talk of the CS and PF coils, whereas in Fig. 10(b) only the contribution of the eddy currents is considered. The latter is then relevant when considering the output signal of the CER, after applying a compensation technique. In fact, the ideal CS/PF cross talk and the additional CS/PF cross talk due to CER imperfections can be compensated (see [23] and references

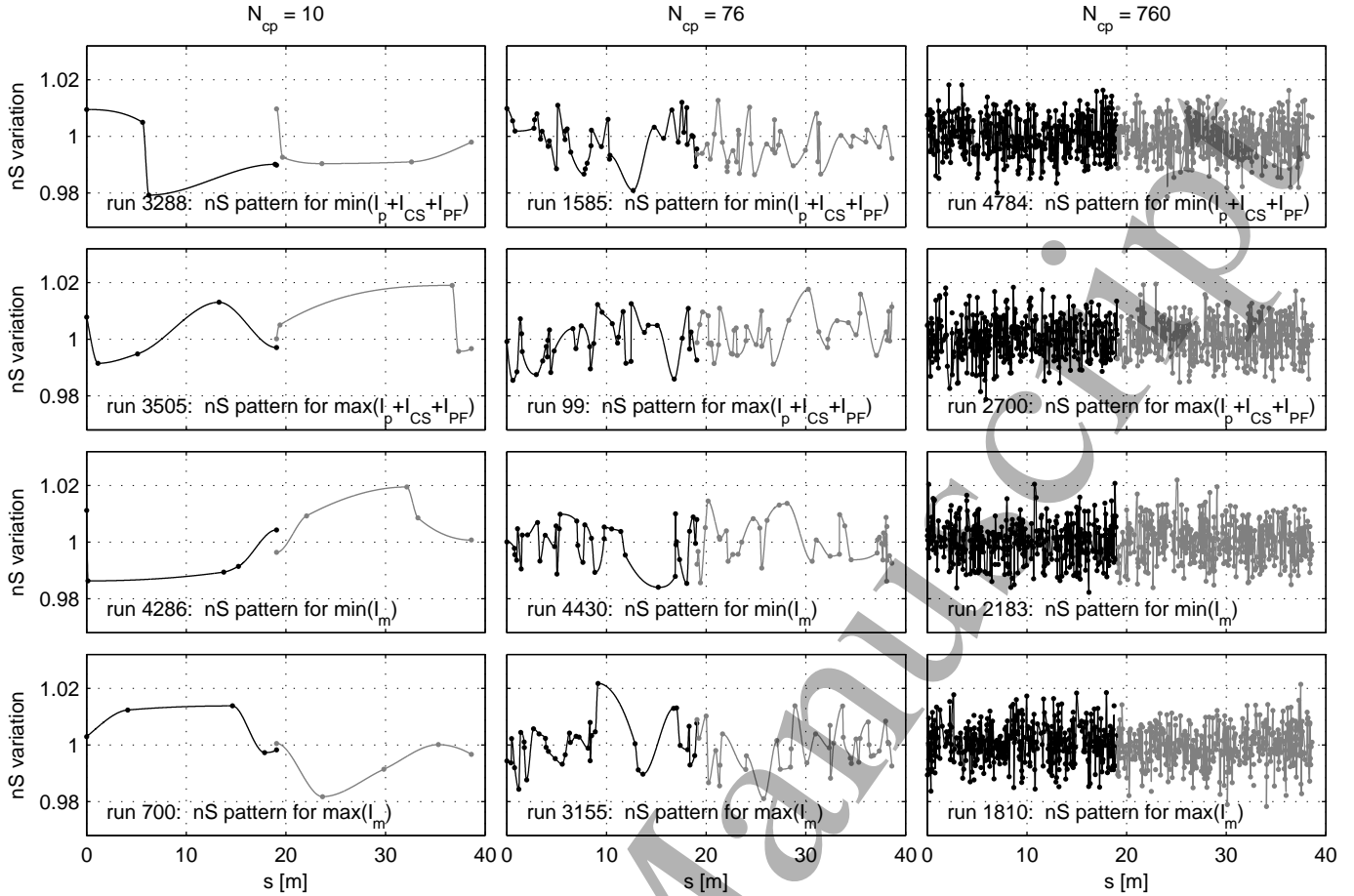


Figure 7: Patterns corresponding to the minimum and maximum measurement error on the output of the CER signal in a statistical set consisting of 5000 runs, in the case of flat-top plasma configuration with presence of the ferromagnetic inserts. The local gain  $nS$  is randomly varying, while the other parameters are set to the values they have in ideal geometry. The plots in the first and second rows refer to the contribution of the source plasma+CS+PF, whereas the third and fourth rows consider the FI contribution. For the first, second and third column it is respectively  $f_s \approx 0.2, 2, 20$  control points per meter.

therein). Since the measurement error of the CS/PF current is small (the corresponding  $2\sigma$  is estimated to be 0.2 %), the CS/PF compensation works effectively (0.2 % of the cross talk is negligible). Table 7 reports the total measurement error  $2\sigma$ , parametrised versus the spatial frequency of the geometrical deviations and the maximum tilting angle, in two panels labeled before and after CS&PF compensation. All the geometric effects are considered and act simultaneously and independently. The compensation of the poloidal field currents greatly reduce the measurement error due to the geometric non-idealities of the device, which is thus below 1 % even for the limit/unrealistic values of the parameters. The error for realistic values of the CER geometric imperfection parameters should be less than 0.33 %. This value might still be conservative, however there are no absolute certainties on that, as it will depend on the final properties of the as-installed CER cables.

Notice that the calculated errors before compensation at  $t = 0$  are not the same as for the flat-top configuration we analysed in the previous section (Table 5). This is because

the poloidal field currents are different.

Figure 11 shows the error distributions of the flat top configuration considered in Table 7 for  $f_s = 2 \text{ m}^{-1}$  and  $\theta_{\text{max}} = 3\sigma_\theta = 4 \text{ deg}$ . The gray and black histograms correspond to the errors before and after CS&PF compensation, respectively.

The results of the present section remain valid for the more general MD UP scenario, where a toroidal field variation is present as well, because these effects are less important.

## 11. Computation of the measurement error at low range

We assess now the measurement accuracy at low current values, in particular in the low operating range, defined by the condition that the total toroidal current and the maximum measurement error don't exceed 1 MA and 10 kA, respectively (see (1)).

The CER works in the low measurement range only during breakdown, hence we consider a typical breakdown &

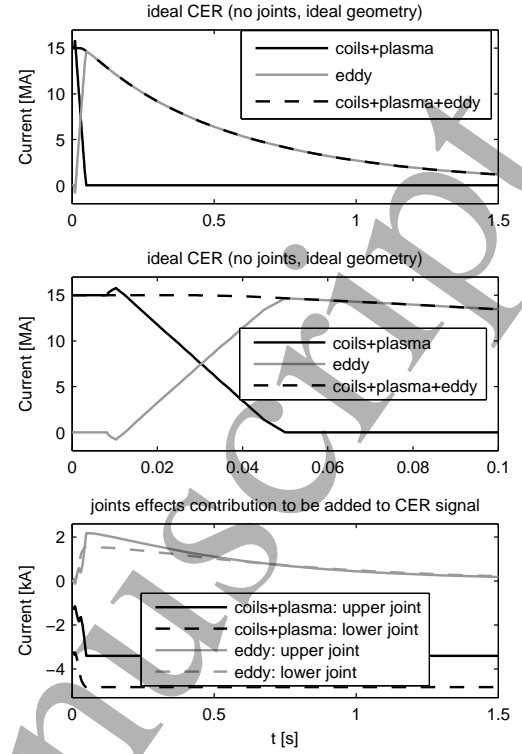
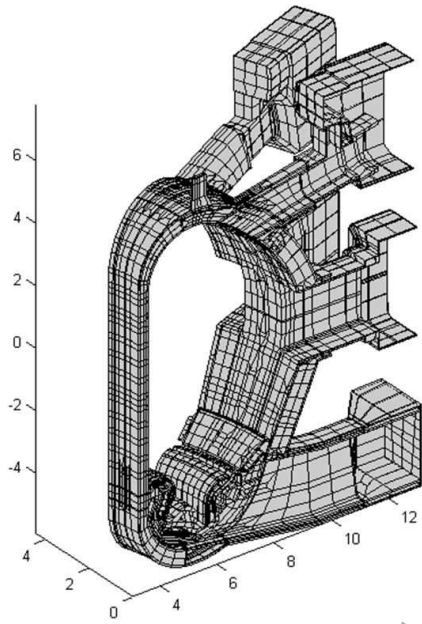
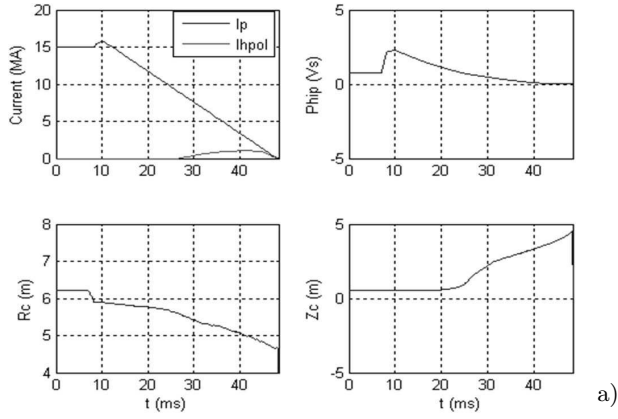


Figure 9: Contributions to the calculated CER output in ideal geometry for the MD UP PFV scenario. The middle plot gives a zoomed view of the top one in the range 0–100 ms. When  $I_p$  start decreasing, the eddys start to rise so that their sum, namely the CER output, remains approximately constant during the event. Hence the CER cannot be used as a direct measure of  $I_p$  in general conditions. More specifically, from the first plot one can estimate of the VV toroidal time constant as  $\tau_{VV} \approx 0.5$  s. Thus, during transient or fast events, the CER become aware of them  $\sim 0.5$  s after they arise. The CER is not intended to be used during transients. The reference estimate of  $I_p$  for operation is provided by the in-vessel tangential coils [9].

Figure 8: a) The MD UP PFV scenario.  $I_p$  and  $I_{hpol}$  are the plasma and the poloidal halo currents respectively. The former decreases rapidly from 15 MA to zero.  $\Phi_p$  is the diamagnetic flux, and  $R_c$ ,  $Z_c$  give the position of the plasma current centroid. b) numerical model.

ramp-up scenario. As seen in § 9–10, the shielding of the VV and the properties of Rogowski sensors, imply that this analysis is fully sufficient to assess the performances at low range. Figure 12 shows the time evolution of the plasma current, the eddy current and their sum, calculated as line integral of the corresponding magnetic field along the CER path in ideal geometry. Relevant instants of interest are (time expressed in seconds, current in MA):

- Breakdown ( $0 < t < 0.900$ ):
  - $t = 0.081$ :  $I_p = 0$ ,  $I_{tot} = I_{eddy} = 0.5$
  - $t = 0.198$ :  $I_p = 0$ ,  $I_{tot} = I_{eddy} = 1.0$
  - $t = 0.765$ :  $I_p = 0$ ,  $I_{tot} = I_{eddy_{max}} = 1.88$
- Ramp-up ( $0.900 \leq t$ ):
  - $t = 0.900$ :  $I_p = 0$ ,  $I_{tot} = I_{eddy} = 1.79$

$$- t = 1.300: I_p = 0.5, I_{tot} = 1.73$$

$$- t = 1.833: I_p = 1.0, I_{tot} = 1.54$$

Figure 13 reports the poloidal field coil currents throughout the scenario. We notice that, during breakdown and ramp-up, while the total toroidal current is small, most of the CS&PF currents are large (only PF2-PF5 are not that large). Hence, before poloidal field coils compensation, the statistical error is expected to be relatively high. That is indeed the case, as quantitatively shown in Table 8, which reports the total measurement error  $2\sigma(\cdot)$ , parametrised versus the spatial frequency of the geometrical deviations and the maximum tilting angle, in two panels labeled *before* and *after* CS&PF&VS3 compensation. All the geometric effects are considered and act simultaneously and independently. The after compensation error values are calculated by considering only the magnetic field due to the plasma and the eddy currents. Therefore, since in this scenario the VS3 currents are also activated, to be rigorous we mention that the compensation procedure targets the VS3 coils too. In fact, although the VS3U and VS3L coils are connected in anti-series, the

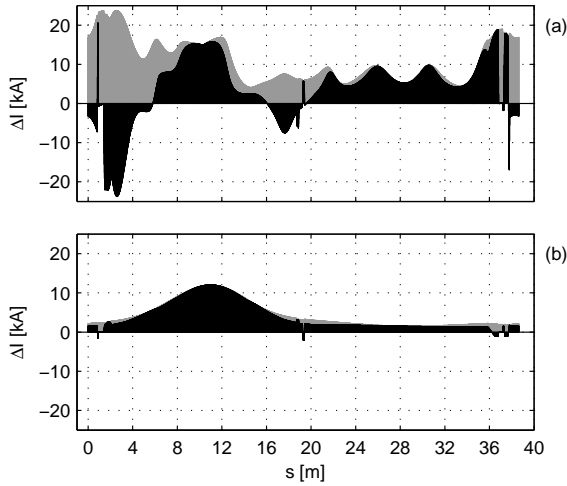


Figure 10: Elemental contributions to the CER signal in ideal geometry, as functions of the poloidal location, in the MD UP PFV scenario. The configuration considered is the one at the instant  $t = 50$  ms, where the eddy currents provide the maximum effect,  $\mathcal{I} = \mathcal{I}_{\text{eddy}} = 14.7$  MA, and it is  $\mathcal{I}_p = 0$ . In a) the contributions of both the eddy currents and the poloidal field coils are considered, while in b) the eddies act alone. The bar graphs in gray and black color represent the magnitude of the local field  $|\mathbf{H}|\Delta s$  and the aliquot which contribute to the CER signal in ideal geometry  $\Delta I = \mathbf{H} \cdot \hat{\mathbf{t}} \Delta s$ , respectively.

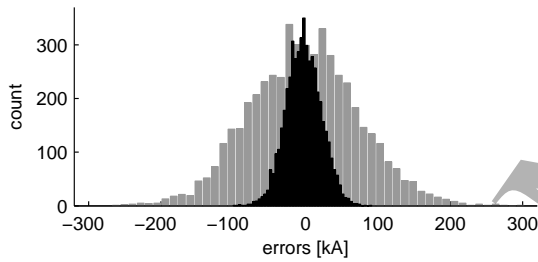


Figure 11: Error distributions of the MD UP PFV configuration at  $t = 50$  ms considered in Table 7, for  $f_s = 2 \text{ m}^{-1}$  and  $\theta_{\text{max}} = 3\sigma_\theta = 4$  deg. The histogram in gray colour correspond to the errors obtained by considering the combined effects of the eddy currents and the CS&PF coils; the one in black colour takes into account the eddies only, hence it refers to the actual error after CS&PF compensation.

non-ideality of the CER implies that the error before compensation depends upon  $I_{\text{VS3}}$  as well. This effect amount to a fraction of a kA at the maximum  $I_{\text{VS3}}$  in pulsed condition, which, compared to the error due to the PF&CS coils, is very small.  $I_{\text{VS3}}$  is quite small at  $t = 0.081$  s, hence the error due to possibly uncompensated VS3 would be negligible, as follows for comparison with the after compensation error at the beginning of the breakdown (Table 8).

During the low measurement range of the breakdown phase, the plasma current is zero and thus the CER output is only due to the eddy currents. The corresponding measurement error for realistic values of the CER geometric imperfection parameters is, according to Table 8, expected to be less than 40 kA. This value might still be conservative, however there are no certainties on that, as it will depend on the final properties of the as-installed

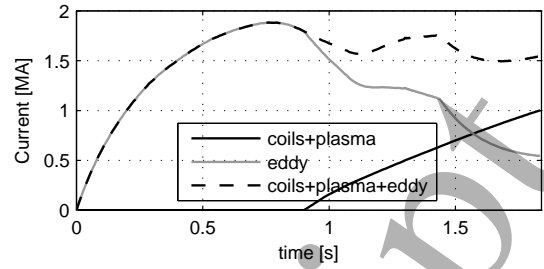


Figure 12: Time evolution of the plasma current, the eddy current and their sum, in the considered breakdown & ramp-up scenario, calculated as line integral of the corresponding magnetic field along the CER path in ideal geometry and without joints. The field used to calculate the plasma current includes the contribution due to the currents flowing in the CS/PF coils which, however, have no effect, for those coils are external to the CER path. The VS3 coils give no contribution as well (exactly only in ideal geometry and without joints), since they are connected in anti-series.

CER cables. The same result,  $2\sigma < 40$  kA, holds for the remaining part of the breakdown and during ramp-up as well.

The measurement error can however dramatically be reduced. As already noticed, in fact, the ideal CS/PF/V3 cross talk and the additional CS/PF/V3 cross talk due to CER imperfections can be compensated. The effects of the CS/PF/V3 currents on the FI gets compensated too, because, as explained in § 9.2, for the FI the equivalent linear poloidal permeability model holds. As seen in the previous section, since the  $2\sigma$  parameter of the CS/PF/V3 current measurement is small, the compensation works effectively. The other effects due to CER non-idealities and to the FI, are roughly proportional to the plasma current and to the toroidal vessel current (hence they decrease when the total toroidal current gets smaller). Then, after performing the poloidal field coils compensation, even when considering the unrealistic cases (8 deg of maximum tilt and/or  $f_s = 0.2$ ), the statistical error is within specification (Table 8).

Figure 14 represents the contributions to the CER signal at all the poloidal locations for the time instants corresponding to the breakdown and ramp-up configurations considered in Table 8, after CS/PF/V3 compensation. The gray plots show the magnitude of the local magnetic field, whereas the black ones are the aliquot which contribute to the CER signal in ideal geometry.

We notice that the result  $2\sigma$  equal or less than about 0.30 % shown in Table 8 holds for the flat top and max eddy configurations analysed in § 9–10 as well. Hence such result is a general property of the CER diagnostic. As anticipated, this is due to the fact that well engineered loop Rogowski sensors provide a reliable measure of the total enclosed current, and the measurement error is approximately uniform regardless of the specific current density distribution. Our analyses confirms such property and consents qualitative and quantitative assessments.



Configuration	Breakdown			Ramp-up														
	$t = 0.081$ s $I_p = 0$ $I_{\text{eddy}} = 0.5$ MA	$t = 0.198$ s $I_p = 0$ $I_{\text{eddy}} = 1$ MA	$t = 0.765$ s $I_p = 0$ $I_{\text{eddy}}^{\text{max}} = 1.88$ MA	$t = 1.300$ s $I_p = 0.5$ MA $I_{\text{eddy}} = 1.23$ MA $I_{\text{tot}} = 1.73$ MA				$t = 1.833$ s $I_p = 1$ MA $I_{\text{eddy}} = 0.54$ MA $I_{\text{tot}} = 1.54$ MA										
Total statistical error (5000 runs) due to all geometric deviations ( $\Delta\kappa_{\text{max}} = 3\sigma_{\kappa} = 0.02$ , $\delta_{\text{max}} = 3\sigma_{\delta} = 0.5$ mm, $\theta_{\text{max}} = 3\sigma_{\theta}$ parameter)																		
Before CS & PF & VS3 compensation																		
	$2\sigma(\mathcal{I}_p + \mathcal{I}_{\text{eddy}} + \mathcal{I}_{\text{coils}})$ [kA] (low range)						$\frac{100 \cdot 2\sigma(\mathcal{I}_p + \mathcal{I}_{\text{eddy}} + \mathcal{I}_{\text{coils}})}{\mathcal{I}_p + \mathcal{I}_{\text{eddy}} + \mathcal{I}_{\text{coils}}}$ [%]											
2°	27	25	9.5	25	25	18	9.3	1.4	1.2	0.47	1.39	1.34	0.95	0.50	1.60	1.47	1.05	0.55
4°	47	43	16	45	41	30	16	2.2	2.1	0.78	2.30	2.25	1.61	0.84	2.67	2.47	1.77	0.95
8°	91	81	30	86	79	57	29	4.2	3.9	1.5	4.34	4.28	3.07	1.59	5.05	4.70	3.37	1.75
After CS & PF & VS3 compensation																		
	$2\sigma(\mathcal{I}_{\text{eddy}})$ [kA] (low range)						$\frac{100 \cdot 2\sigma(\mathcal{I}_p + \mathcal{I}_{\text{eddy}})}{\mathcal{I}_p + \mathcal{I}_{\text{eddy}}}$ [%]											
2°	3.7	1.4	0.43	7.3	2.7	1.7	0.84	0.72	0.27	0.08	0.73	0.27	0.17	0.08	0.75	0.29	0.18	0.09
4°	3.8	<b>1.5</b>	0.48	7.5	<b>2.9</b>	1.9	0.94	0.75	<b>0.30</b>	0.10	0.76	<b>0.30</b>	0.19	0.10	0.78	<b>0.32</b>	0.21	0.10
8°	4.3	1.9	0.64	8.5	3.8	2.5	1.3	0.86	0.40	0.13	0.87	0.41	0.26	0.13	0.91	0.44	0.28	0.14
$\theta_{\text{max}} = 3\sigma_{\theta}$	0.2	2	20	0.2	2	<b>5</b>	20	0.2	2	20	0.2	2	<b>5</b>	20	0.2	2	<b>5</b>	20
$\approx f_s = \frac{1}{(\Delta s)} [\text{m}^{-1}]$																		

Table 8: Calculated measurement error  $2\sigma(\cdot)$  for the considered breakdown & ramp-up scenario, parametrised versus the spatial frequency of the geometrical deviations and the maximum tilting angle, before and after CS/PF/Vs3 compensation. The values in italic font correspond to the limit region of the parameters that we consider unrealistic, whereas those values in bold are a sensible upper bound estimate of the error due to the CER geometric imperfections. For completeness we state that the calculation were performed with the worst case joint configuration (10+10 mm).

## 12. Computation of the measurement error: effect of toroidal field variations

In this section we assess whether the variations of the toroidal field (TF) caused by the plasma paramagnetism (ramp-up at low beta-poloidal) and subsequent diamagnetism (heating to high beta) could affect the CER measurement. In fact it is not a-priori clear if such variations are effectively eliminated by the TF power supply. If not, the possibility for pick-up effects, especially due to the non-ideality of the CER, arises.

The CER lies on the external perimeter of the TF coil, mostly in its poloidal symmetry plane. Since the TF solenoid is not toroidally continuous, the field due to the TF current along the CER path is not negligible.

The solenoid is not very far from being toroidally continuous in the inward region. Thus the field at the CER location in such region is much less than 1 T at  $I_{\text{TF}} = 68$  kA, which is the TF coil nominal current [13, 16]. The field is instead much stronger (more than 3 T at  $I_{\text{TF}} = 68$  kA) in the external part of the outward region. These fields estimates have been obtained with both simple filamentary models and accurate 3D calculations, which resulted to be in good agreement with each other.

Only a fraction  $F$  of the TF field at the maximum  $I_{\text{TF}}$  current value has to be considered in order to calculate the CER measurement error due to the possible non-ideal rejection properties of the TF power supply. The following considerations consent to estimate  $F$ .

The maximum plasma diamagnetic flux [25] (with poloidal beta  $\beta_{\text{pol}} = 3$ ) is  $\Phi_p = 3.6$  Vs, whereas the flux linkage with one turn of the TF coil is about 500 Vs at  $I_{\text{TF}} = 68$  kA. The ratio between this flux and  $\Phi_p$  is then more than 100, and thus a maximum  $\Phi_p$  variation will not cause more than a 1%  $I_{\text{TF}}$  variation. Hence we can take  $F = 0.01$  but this is a very conservative assumption.

The field is mostly toroidally directed (this is less true in the lower feedout region only), hence it is perpendicular to the CER path. The pick-up is then essentially due to turns tilting, and not much by the local gain (pitch and cross section) variations. The centricity effect also implies pick-up of perpendicular field, but, as repeatedly remarked, it is less significant than the tilting.

Like in the previous sections, the measurement error is calculated by assuming: the maximum centricity deviation,  $\delta_{\text{max}} = 3\sigma_{\delta} = 0.5$  mm; the maximum local gain deviation,  $\Delta\kappa_{\text{max}} = 3\sigma_{\kappa} = 2\%$ ; the maximum tilting angle,  $\theta_{\text{max}} = 3\sigma_{\theta} = \{2, 4, 8\}$  deg. 8 deg is considered a limit and unrealistic value. For smaller (or larger, but not too much larger) tilting angles, the error scales linearly with very good approximation.

Many statistical analyses were performed, each of which considers a different value of the spatial frequency of the geometric variations,  $f_s$ , and the three geometric deviation types, acting both separately and simultaneously. Tilting is indeed predominant. The worst result gives an error  $2\sigma = 14$  kA. It corresponds to  $f_s = 0.2$  control points per meter (and  $\theta_{\text{max}} = 8$  deg), implying a local system-

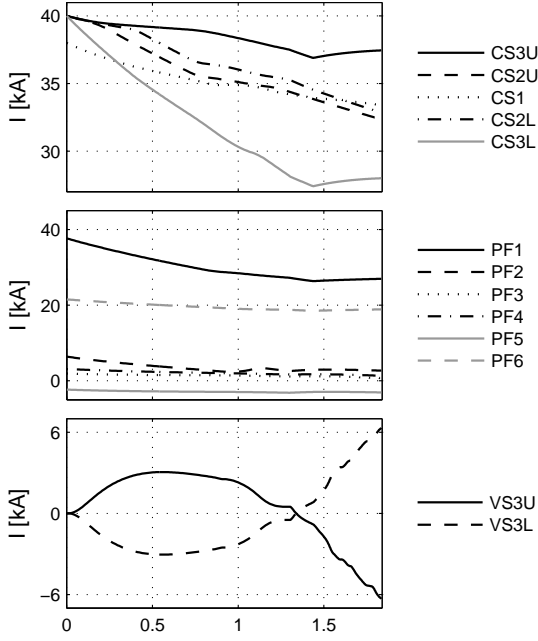


Figure 13: Currents in the poloidal field coils for the considered breakdown & ramp-up scenario.

atic tilting effect, which is unlikely to happen. A more realistic case is with  $f_s = 2$  control points per meter and  $\theta_{\max} = 4$  deg, for which the error is  $2\sigma = 2.5$  kA. Detailed numerical results are reported in [13].

### 13. Calibration

A specific scenario and the procedure for the calibration of the CER are in progress to be defined and agreed [10]. In this section we describe the relevant work performed during the design review activities of the diagnostic [24]. Further studies will be carried out in the future.

A natural way to perform the calibration of the diagnostic is to use the VS coils, acting one at a time or in co-series, because they are internal to the whole CER loop (Fig. 4). However, since the CER is constituted of two parts, T Todd proposed to calibrate the two halves separately, by using the external CS and PF coils. This idea dates back to the original Chattock's proposal [1], later reissued by Rogowski and Steinhaus [2, 3], who meant the sensor as a general open device, and not necessarily a closed loop. We refer to the two calibration types as VS3 calibration and split calibration. The latter conveys the following advantages:

- the signals are much larger than those available when using the VS3 coils (Table 9);
- better compliance: simultaneously recording the three analog signals (inboard CER, outboard CER and their sum), or acting on the CER connections is less dangerous or at least much simpler than acting on the VS3 coils configuration (co-series, anti-series);

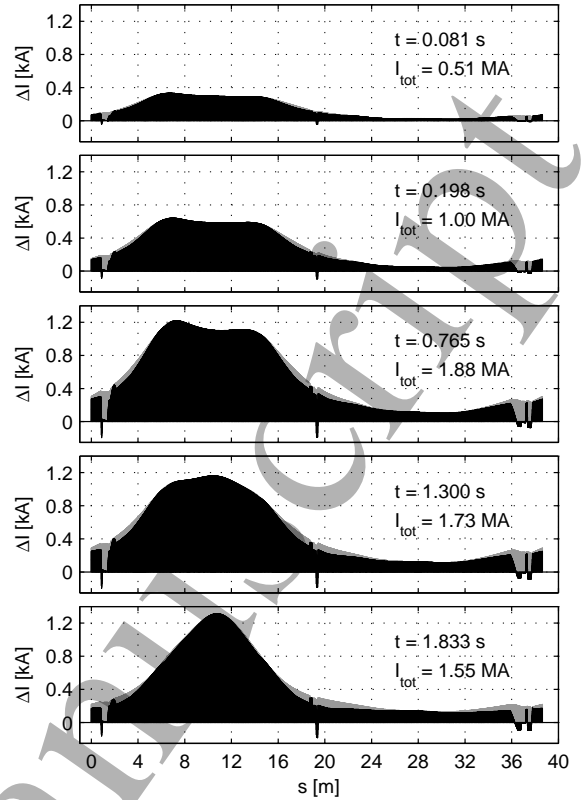


Figure 14: Elemental contributions to the CER signal in ideal geometry, as functions of the poloidal location, in the considered breakdown & ramp-up scenario. The bar graphs in gray and black color represent the magnitude of the local field  $|H|\Delta s$  and the aliquot which contribute to the CER signal in ideal geometry  $\Delta I = \mathbf{H} \cdot \hat{\mathbf{t}} \Delta s$ , respectively. The configuration considered are those for which quantitative results are reported in Table 8 (after CS&PF&VS3 compensation panel). The different shapes and magnitudes in the five plots reflect the eddy and plasma current distribution. Despite these differences, the measurement error is always approximately the same.

- suitable combinations of CS/PF currents can provide indications of local CER imperfections after installation;
- the calibration with the VS3 coils connected in series instead of anti-series is feasible anyway.

A deviation from the ideal path would not have any relevant effect. In fact, the ideal and the real CER paths (inboard/outboard) constitute closed loops which do not link any current (Fig. 15). Hence the line integral only depends on the initial and final ends of the CER cable, i.e., the locations of the joints, and a survey of the as-installed CER is not needed. The need of knowing the exact location of the joints is relevant only with reference to the very close coils (mainly PF6 and PF1).

The non-ideal geometric configuration of the CS and PF coils may impact the accuracy of the split calibration method. With respect to that, an ad-hoc dry run would allow to calibrate using 11 independent sources (5 CS and 6 PF coils), which would reduce the rms error by a factor of more than three, not to mention that the two halves

Ideal CER & ideal coils geometry, CER with 10+10 mm joints											
Coil	N (turns)	$I_{\max}$ [kA]	$NI_{\max}$ [MA]	Gauss points	Absolute outputs				Gains		
					inboard $\dot{\mathcal{I}}_i$	balanced $\frac{\dot{\mathcal{I}}_i - \dot{\mathcal{I}}_o}{2}$ [kA]	outboard $\dot{\mathcal{I}}_o$	full $\dot{\mathcal{I}}$	inboard $\frac{\dot{\mathcal{I}}_i}{NI_{\max}}$	outboard $\frac{\dot{\mathcal{I}}_o}{NI_{\max}}$ [kA/MA]	full $\frac{\dot{\mathcal{I}}}{NI_{\max}}$
CS3U	553	45	<b>24.885</b>	3 · 6	-225.99	<i>-225.56</i>	+225.12	-0.87	-9.0814	+9.0465	-0.035
CS2U	553	45	<b>24.885</b>	3 · 6	-339.30	<i>-338.78</i>	+338.27	-1.03	-13.635	+13.593	-0.041
CS1	1106	45	<b>49.770</b>	3 · 12	-669.55	<i>-668.83</i>	+668.11	-1.44	-13.453	+13.424	-0.029
CS2L	553	45	<b>24.885</b>	3 · 6	-296.37	<i>-296.00</i>	+295.62	-0.75	-11.910	+11.879	-0.030
CS3L	553	45	<b>24.885</b>	3 · 6	-202.98	<i>-202.69</i>	+202.40	-0.58	-8.1566	+8.1333	-0.023
PF1	248.6	48	11.933	4 · 4	<i>+254.08</i>	<i>+252.49</i>	<i>-250.89</i>	+3.19	+21.293	<i>-21.025</i>	+0.268
PF2	115.2	55	6.336	2 · 2	+2950.0	<b>+2950.1</b>	-2950.3	-0.30	<b>+465.59</b>	<b>-465.64</b>	-0.047
PF3	185.9	55	10.225	2 · 2	+5237.7	<b>+5238.4</b>	-5239.1	-1.45	<b>+512.27</b>	<b>-512.41</b>	-0.142
PF4	169.9	55	9.345	2 · 2	+5062.8	<b>+5063.7</b>	-5064.5	-1.71	<b>+541.80</b>	<b>-541.98</b>	-0.183
PF5	216.8	52	11.274	3 · 3	+5323.2	<b>+5324.0</b>	-5324.9	-1.66	<b>+472.18</b>	<b>-472.33</b>	-0.147
PF6	459.4	52	<b>23.889</b>	5 · 4	<i>-49.450</i>	<i>-50.807</i>	<i>+52.163</i>	+2.71	-2.0700	+2.1836	+0.114
VS3U	4	10 <sup>†</sup>	0.040	1	<i>30.816</i>		<i>9.154</i>	<i>39.969</i>	770.39	228.84	999.23
VS3L	4	10 <sup>†</sup>	0.040	1	<i>30.073</i>		<i>9.914</i>	<i>39.987</i>	751.82	247.86	999.68
Ip*	1		<b>20</b>	1	16730.1		3265.3	19995.5	836.51	163.27	999.77

<sup>†</sup> VS3 steady state max rms current [13, 16], available for both operation (anti-series connection) and calibration (co-series or parallel)

\* Modeled with a single filament @  $[r, z] = [6.054, 0.474]$  m (average of target separatrix points)

Table 9: Inboard, outboard and full CER outputs, due to the external and internal axisymmetric coils, in ideal geometry and at maximum nominal currents. Quantities are calculated with the *simple model*. Specifically, for the inboard and outboard CER, line integral along straight lines connecting the joints are performed (Fig. 4). For the full CER, the field at the joints only is considered for the external coils, whereas for the threaded sources (VS3U-L & Ip) the field at the joints gives a correction. The values represented with bold font in the central and right panels refer to the sources (PF2–PF5) which provide the largest outputs and sensitivities, and which are not the ones with the largest available  $NI_{\max}$  (bold in left panel). The latter provide instead comparatively small outputs (italic font). PF1 and PF6 also provide small outputs, which moreover show appreciable inboard vs outboard differences.

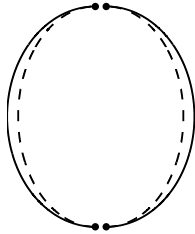


Figure 15: Schematization of the ideal and real path of the CER

provide two opposite signals. We shall however see that this is likely not needed, because the non-ideal configuration of certain coils (PF3, PF4 and CS1) has very little impact.

In order to compare the two calibration methods, namely using the CS/PF vs using the VS3 coils, we need to calculate the inboard, outboard and full CER output due to each poloidal field source. That means calculating line integrals along the inboard and outboard CER path. We recall Fig. 5, which shows the elemental contributions to the CER signal in ideal geometry due to all the sources as functions of the poloidal location along the CER path.

Alternatively to the CER path, equivalent integration paths can be used, the simplest being piecewise straight lines connecting the end of the joints (see Fig. 4). To perform the analysis, we then use the following *simple model*:

- for non-threading sources (CS and PF coils):

$\dot{\mathcal{I}}_i$  &  $\dot{\mathcal{I}}_o$ : ideal inboard & outboard CER outputs, calculated as line integral along straight lines ending at the joints;

$-\dot{\mathcal{I}}_i + \dot{\mathcal{I}}_o + \dot{\mathcal{I}}_j = 0$  ( $\dot{\mathcal{I}}_j$  = line integral along upper + lower joints);

$-\dot{\mathcal{I}}_{\text{split}} = \dot{\mathcal{I}}_i + \frac{\dot{\mathcal{I}}_j}{2} = -\dot{\mathcal{I}}_o - \frac{\dot{\mathcal{I}}_j}{2} = \frac{\dot{\mathcal{I}}_i - \dot{\mathcal{I}}_o}{2} = \frac{\dot{\mathcal{I}}_i}{|\dot{\mathcal{I}}_i|} \frac{|\dot{\mathcal{I}}_i| + |\dot{\mathcal{I}}_o|}{2}$ : balanced quantity, obtained by adding half of the ‘missing’ fluxes at the joints;

$-\dot{\mathcal{I}} = \dot{\mathcal{I}}_i + \dot{\mathcal{I}}_o = -\dot{\mathcal{I}}_j$ : full CER output (for which only the field at the joints matters);

- for threading sources:

$-\dot{\mathcal{I}} = \dot{\mathcal{I}}_i + \dot{\mathcal{I}}_o$ : full CER output ( $\dot{\mathcal{I}} = NI - \dot{\mathcal{I}}_j$  for VS3 coils and  $\dot{\mathcal{I}} = I_p - \dot{\mathcal{I}}_j$  for plasma; the field at the joints gives a small correction to the threaded current).

We remark that the quantities considered in the simple model are computed with the canonical model (5), namely without considering the CER imperfections. This is adequate because the effect of the CER imperfections on the output signals in calibration and in measure mode are correlated and don’t have to be considered twice. This can be explained as follows. The calibrated measure is  $Y = \mathcal{I}/k$ , where  $k$  is the calibration coefficient obtained by performing a specific calibration scenario, e.g. a dry run

Ideal CER with 10+10 mm joints						
Coil	Perturbed geometry of poloidal field sources					
	Vertical shift $\Delta z$ [mm] $\pm 10$	Horizontal shift			Tilt $\Delta z_{\max} = -5$ mm @ $\phi$ [deg]	
		$\Delta x$ [mm] $\pm 5$	$\Delta y$ [mm] +5   -5	0, 180	+90	-90
	Percent variation on <i>split</i> CER calculated outputs, $\Delta \tilde{I}_i, \Delta \tilde{I}_o$ [%]					
CS3U	$\mp 0.41$	$\pm 0.18$	$\pm 0.002$	$\pm 0.69$	$\mp 0.005$	
CS2U	$\mp 0.05$	$\pm 0.15$	$\pm 0.002$	$\pm 0.25$	$\mp 0.005$	
<b>CS1</b>	$\pm 0.02$	<b><math>\pm 0.11</math></b>	$\pm 0.004$	$\pm 0.02$	$\mp 0.01$	inboard CER
CS2L	$\pm 0.08$	$\pm 0.13$	$\pm 0.009$	$\mp 0.22$	$\mp 0.02$	
CS3L	$\pm 0.32$	$\pm 0.14$	$\pm 0.01$	$\mp 0.56$	$\mp 0.05$	or outboard CER
PF1	$\pm 1.8$	$\pm 0.68$	$\mp 0.002$	$\mp 1.3$	$\pm 0.002$	
PF2	$\mp 0.19$	$\mp 0.01$	$\mp 3e-4$	$\pm 0.07$	$\pm 1e-4$	
<b>PF3</b>	$\mp 0.05$	$\mp 0.02$	$\mp 6e-4$	$\pm 0.01$	$\mp 2e-4$	
<b>PF4</b>	$\pm 0.03$	$\mp 0.02$	$\mp 0.001$	$\mp 0.009$	$\mp 0.001$	
PF5	$\pm 0.22$	$\mp 0.02$	$\mp 0.001$	$\mp 0.09$	$\mp 0.007$	
PF6	$\pm 19$	$\mp 2.8$	$\mp 0.26$	$\mp 13$	$\mp 1.1$	inboard CER
	$\pm 18$	$\mp 2.6$	$\mp 0.24$	$\mp 12$	$\mp 1.1$	outboard CER
	Percent variation on <i>full</i> CER calculated output, $\Delta \tilde{I}$ [%]					
VS3U <sup>†</sup>	$\mp 4e-4$	$\pm 5e-5$	$-2e-7$ $+3e-7$	$\pm 2e-4$	$+3e-8$	$-8e-8$
VS3L <sup>†</sup>	$\pm 6e-5$	$\pm 2e-5$	$\mp 1e-6$	$\mp 2e-5$	$\mp 2e-6$	

<sup>†</sup> Modeled with a single filament

Table 10: Output variations of the ideal CER due to non-ideal geometric configurations of the current sources. Values represented with bold font qualify the coils which are particularly suitable to be used for split calibration. Framed values refer to errors larger than 0.5 %.

with known current flowing in the VS3 coils. Both  $\mathcal{I}$  and  $k$  deviate from their ideal values  $\tilde{\mathcal{I}}$  and  $\tilde{k} = 1$ . Since both deviations have the same physical root (the CER geometric nonidealities), an increase in  $\mathcal{I}$  would correspond to an increase in  $k$ . The relative deviation on the calibrated output is  $\frac{\Delta Y}{Y} = \frac{\Delta \mathcal{I}}{\mathcal{I}} - \frac{\Delta k}{k}$ . The statistical error on  $Y$  in terms of its standard deviation is then  $\sigma_Y = \sqrt{\sigma_{\mathcal{I}}^2 + \sigma_k^2 - 2c\sigma_{\mathcal{I}}\sigma_k}$  where  $c$  is the correlation coefficient. The ideal and unrealistic cases of full correlation and incorrelation provide  $\sigma_Y = |\sigma_{\mathcal{I}} - \sigma_k|$  and  $\sigma_Y = \sqrt{\sigma_{\mathcal{I}}^2 + \sigma_k^2}$ , respectively. In the (unreasonable) latter case,  $2\sigma_{\mathcal{I}} \approx 2\sigma_k \approx 0.3\%$  (Table 8) would give  $2\sigma_Y \approx 0.4$ , while the former implies quite a small error. Then the estimate of the total measurement error as given in § 15 is correct. As stated, a complete quantitative analysis of this matter will be carried out in the framework of a future study, after the calibration procedure is defined.

Table 9 reports the quantitative details for the case where the poloidal field coils are in their ideal geometric configuration. The magnetic fields were calculated by considering an optimal number of gauss points, as shown in Fig. 4. The absolute outputs correspond to the maximum available currents [13, 16]. The lower part of the table mainly accounts for the calibration using the threading VS3 coils, whereas the other results are especially interesting when considering the calibration with the non-threading CS&PF coils. The coils with the largest sensitivities (right part of Tab. 9) are PF2–PF5, which show about 50 times higher values than the other CS/PF coils (despite the larger  $NI_{\max}$  available to the latter). In turn, the ab-

solute outputs of the other CS/PF coils are an order of magnitude higher than the VS3 coils. Hence, as expected, comparatively the VS3 coils produce very small absolute outputs. The outputs of the inboard and outboard CER parts are roughly coincident for all the external coils but PF1 and PF6, which are the closest to the joints. It is then advisable to use in general the reported balanced signal, namely the algebraic average of the two outputs which, as seen, is analytically the same of e.g. the sum of the inboard signal plus half of the ‘missing’ fluxes at the upper and lower joints.

The results shown in Tab. 9 also highlight the fact that different sources give output CER signals with very different magnitudes. In particular, the output due to the VS3 coils is in the kA range, to be compared to the MA range which is typical when the CER is in measure mode. This is to be taken into account for the design of the data acquisition cards, in order not to lose numerical accuracy in calibration mode.

Since a huge number of other magnetic diagnostics are available in the ITER machine (in particular internal and external pick-up coils and saddle loops), it is certainly possible to have a good knowledge of the field along a path connecting the initial and final ends of half CER. With reference to that, it is important to characterize the sensitivity of the CER signals with respect to the real location of the sources (the 11 CS and PF coils). A quantitative analysis has thus been performed to determine the variation of the outputs of the two half CER and of the full CER due to the unknown exact geometric configuration of

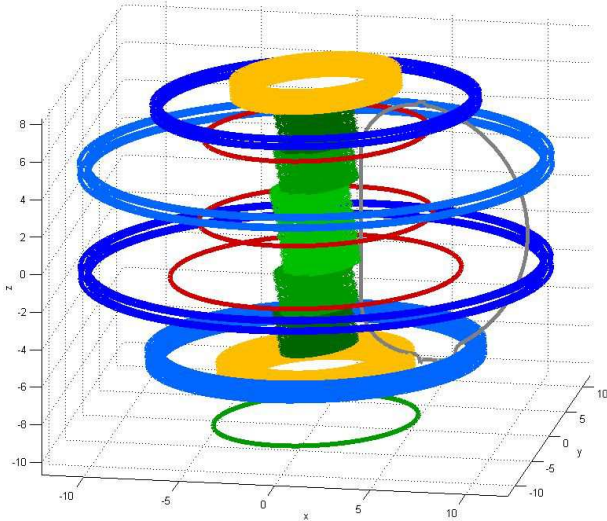


Figure 16: Illustration of the considered poloidal field sources, represented as sets of Gauss filaments (see Fig. 4), in the nonideal case where each coil is tilted of an amount corresponding to an (exaggerated)  $\Delta z_{\max} = -0.3$  m in the azimuthal direction  $\phi = 180$  deg.

the CS/PF/VS3 coils. In particular the following effects were considered:

- i. rigid vertical displacement of each coil of  $\pm 10$  mm;
- ii. rigid horizontal displacement of each coil in the  $x$  and  $y$  direction of  $\pm 5$  mm;
- iii. tilt of each coil with respect to the  $z$  axis of an appropriate angle so that the point of the coil reaching the minimum  $z$  position has a  $\Delta z = -5$  mm with respect to the centre (the calculation was repeated for the cases of the tilt applied in the azimuthal directions  $\phi = \{0, 90, 180, 270\}$  deg;
- iv. independent shift of the upper/lower joints from their ideal location.

Figure 16 shows the considered sources in a tilted configuration, exaggerated for illustrative purposes. The results of the analysis are reported in Tab. 10. In particular, the central part of the table refer to the split inboard/outboard CER output, for which:

- the sources to which correspond the least variation in the outputs of the two half CERs are PF3 & PF4, with errors in the range 0.02 to 0.05 %;
- small variations correspond to CS1 as well, with a maximum deviation of 0.11 % corresponding to a  $\Delta x$  shift of  $\pm 5$  mm;
- split output variations for VS3 coils are not considered, since they won't be normally used for split calibration.

Concerning the full CER output (lower part of the table), we have:

- the non-ideal geometric configuration of the VS3 coils have negligible effects, as expected;

- variations for CS/PF are not considered, since they are not very interesting not even in measure mode, for their effects on full CER output can be compensated.

The variations on the CER outputs due to independent shifts of the upper/lower joints from their ideal location are smaller than the above cases of coils non-idealities for the same  $\Delta x$ ,  $\Delta y$ ,  $\Delta z$  (or of the same order of magnitude when considering the extreme cases, e.g. the output due to the PF6 current and a shift of the lower joint).

To estimate the total calibration error, the  $2\sigma$  parameter corresponding to the poloidal field coils current measurement (estimated to be 0.2 %) has to be considered too. In this respect, the possibility of simultaneously using several independent sources (e.g. PF3, PF4 & CS1) is helpful to reduce this effect. In case of using instead, for instance, only PF4, the corresponding error value to be added (Tab. 10) is negligible. In conclusion, the total calibration error is estimated as being less than 0.3 %, which is smaller than the specification value (0.45 % [10]).

#### 14. Noise and integration drift

The CER should not be affected by nuclear effects due to the shielding of the Vacuum Vessel. The remaining effects to be considered which generate noise are hence those due to the electronics.

As already mentioned with reference to the calibration, the  $2\sigma$  parameter corresponding to the poloidal field coils current measurement is estimated to be 0.2 %.

The drift of the electronic integrator is only relevant in measure mode, and not during the in-situ calibration phase, since the calibration lasts for a short period of time. The target parameter of the electronic integrator which imply integration drift is an input offset voltage of 70  $\mu$ Vs/1000 s ( $2\sigma$ ) [9, 13, 26–28]. Extrapolated at the ITER plasma duration (3600 s) that reads 0.25 mVs which, divided by the ideal sensitivity,  $M_0$  (Tab. 1), gives the maximum drift integration error of 2.6 kA ( $2\sigma$ ).

#### 15. Conclusions

This work provides important contributions to the state of the art of electrical current measurements by means of Rogowski sensors, in general and in particular in the nuclear fusion field, with specific reference to the ITER machine. The approximate canonical model which provides the classical expression to calculate the flux linkage is quantitatively validated. The new formula (6) generalizes the classical one and allows to evaluate the effects of the non-ideal geometry of the winding due to unavoidable imperfect manufacturing. A statistical model is proposed, which consents to compute the expected measurement error. Methods to estimate minimum and maximum error bounds due to the various types of geometrical imperfections are provided too.

	Relative error $r$ ( $2\sigma$ )	Absolute error $\Delta y$	Note
CER geometric non-ideality	< 0.4 %	–	After poloidal field compensation. Actual value will depend on effective properties of the as-installed CER.
Calibration	< 0.3 %	–	
TF variations	–	2.5 kA	Actual value will depend on effective properties of the as-installed CER.
Integrator drift	–	2.6 kA @ 3600 s	Negligible during breakdown (very beginning of pulse).
Total error	< 0.5 %	2.5 kA 3.6 kA @ 3600 s 3.6 kA @ 3600 s	

Table 11: Measurement performance summary of the Continuous External Rogowski

The specification of the Continuous External Rogowski define the maximum measurement error  $2\sigma$  in two different operating ranges (see (1)). The analyses carried out in the paper show that the specifications are met. Many causes of error have been considered, which can be classified as follows:

- irrelevant error sources:

- approximation of the windings as sequences of planar turns: error < 1 ppm;
- presence of the joints: error negligible (small and compensable);
- cross talk of the CS/PF/VS3 coils: it is due to the presence of the joints and to the geometrical deviation of the CER, and in measure mode can effectively be compensated;
- non-ideal geometric configuration of the PF3, PF4 and CS1 coils, which are then particularly suitable to perform the split calibration; also important is the fact that a survey of the as-installed CER is not needed;
- ferromagnetic inserts: incidence of about 20 ppm;
- nuclear effects: error negligible (the CER is shielded by the VV);

- main error sources:

- deviation from ideal geometry of the CER windings:  $2\sigma < 0.4\%$ ;
- calibration (either for VS or split calibration type):  $2\sigma < 0.3\%$ , mostly due to the uncertainty on the poloidal field coils current measurement and less than specification (0.45 %);

- sources of absolute errors, relevant at low range:

- uncertainty due to the TF variations induced by the plasma para/dia-magnetism, conservatively estimated as  $2\sigma = 2.5$  kA (relevant possibly at breakdown/ramp-up and at ramp-down);
- integrator drift:  $2\sigma_{\max} = 2.6$  kA @ 3600 s (relevant at ramp-down only).

Synthetically, the digitally recorded output of the Rogowski can be expressed as:

$$y = y_0(1 + r) + \Delta y \quad (8)$$

where  $y_0$  is the exact value of the total toroidal current being measured,  $r$  is a random variable representing the relative error of the measurement and  $\Delta y$  is the random absolute error, which is due to the drift of the integrator and to TF variations. Table 11 provides the quantitative details of the relevant error sources and of the total measurement error as two times the standard deviation.

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