Calibration of Magnetic Diagnostics on Tokamak GOLEM

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Abstract

Calibration constant for small coil of local toroidal field detection on LFS to central B_T is obtained by direct measurement of this field by 3-D Hall probe and found to be equal to (70.42 ± 0.90). Additionally, two models of B_T across the whole circular cross-section are compared to measured values. This, together with results measurement of deviations from $1/R$ profile of B_T imply stronger B_T ripple. Field of passive stabilization seems to be partially shielded and transformer core seems to be less magnetically active than it should be. One of the used current sensors malfunctioned, and for the second a set of calibration constants is provided to fit to normalized sensor.

1 Introduction

Purpose of this report paper is to provide analytical results of measurements which took place on tokamak GOLEM on 3.3.11. This paper does not contain detailed description of used experimental setup, since these information are provided elsewhere. Analysis is divided among 5 sections, each dedicated to specific analysis. Most important outcomes are summarized at the end of paper.

2 Central B_T Analysis

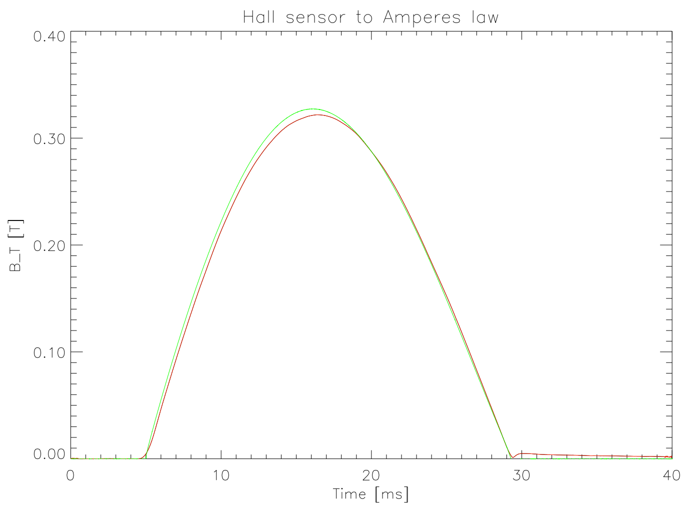

Figure 1: Comparison of toroidal magnetic field (B_T) measured by Hall probe (red) to evolution predicted by Ampere's law (green).

Even though many different phenomena and tokamak properties are investigated in this report, one of (if not 'the') main purposes of this experimental session was to measure toroidal field in the center of tokamak chamber and provide a calibration constant between this field and signal of small coil located on LFS of tokamak used for toroidal field measurement, as this value up until now was never precisely determined since tokamak moved to FNSPE, while being of critical importance. Measurement was hence carried out by a special Hall probe placed in the center of opened tokamak chamber, providing local 3-dimensional resolution of magnetic field. In the setup, magnitude of generated field was gradually increased as the count of shots went. In each of the shots, the signal of Hall probe was compared to integrated voltage present at the ends of coil used for toroidal field measurement. This relation proved to be invariant on magnitude of applied magnetic field and equal to (70.42 ± 0.90) T/Vs, which is the desired calibration constant. It should be noted that this value is rather different from currently used one, which is equal to 87 T/Vs.

During the calibration shots, current in coils of toroidal field generation was measured as well. It was necessary to investigate reliability of data obtained by Hall probe, e.g. how much the measured magnitude of toroidal field corresponded to Ampere's law. Fig. 1 indeed implies that there is a very good agreement between measured field magnitude and the one expected by the common theoretical model. More detailed analysis on toroidal magnetic field profile inside of chamber is provided in following section.

3 B_T Profile Analysis

Model of straightforward application of Ampere's law (e.g. $1/R$ dependency) is widely used to obtain radial profile of toroidal magnetic field inside of tokamak chamber. For D-shaped tokamaks with low aspect ratio, this model seems

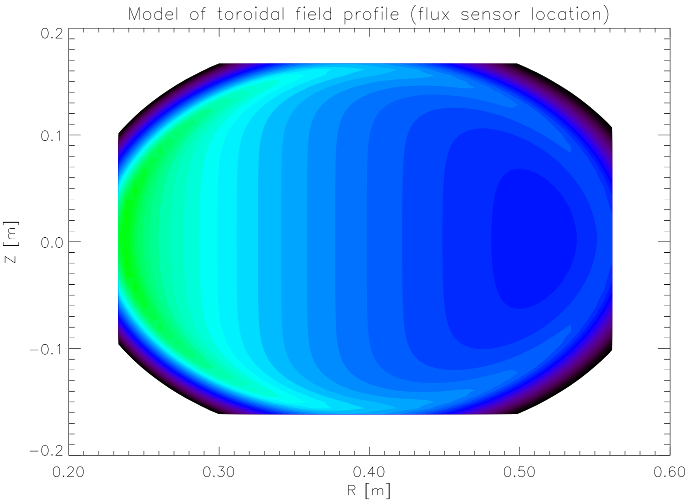

Figure 2: Model of poloidal cross-section located at the position of total toroidal flux sensor (practically right under one of the coils of toroidal field generation). Please note that axes are not to scale to each other.

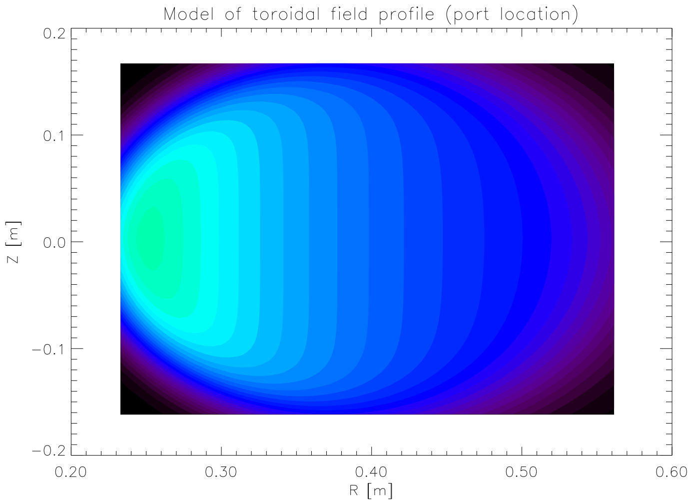

Figure 3: Model of poloidal cross-section located at the position large port with Hall probe in it (practically right between two coils of toroidal field generation). Please note that axes are not to scale to each other.

appropriate as coils of toroidal field generation near central solenoid indeed do resemble long straight conducting wire of large diameter. However, this would not seem to be the cause of circular-shaped tokamaks with high aspect ratio, such as GOLEM. Coils of toroidal field generation encircling its chamber hardly resemble straight conducting wire. Thus a new model of toroidal magnetic field profile across the whole poloidal cross section was made with use of Biot-Savart's law:

$$\vec{B} = \frac{\mu_0}{4\pi} I \oint_l \frac{\mathrm{d}\vec{l} \times \vec{r}}{r^{3/2}}. \tag{1}$$

In the model, the whole poloidal cross section was divided into 60×60 grid and each of the eight loops of every of the 28 coils (e.g 224 conducting loops - each placed in a different location, since finite dimensions of the large coils of B_T generation were not negligible) was divided into 1000 infinitesimal conducting elements. In each point of the chosen grid, the influence of each of 224000 elements in total was calculated so that integral equation 1 could be solved. Results proved to be dependent on relative location of poloidal cross-section to the nearest coil (with respect to chosen poloidal cross-section). Calculated results for experimentally relevant cross-section locations can be seen in fig. 2 and fig. 3. Radial profile corresponding to $Z = 0$ m value on these locations, compared to Ampere's law model is provided in fig. 4 and fig. 5.

From our model, following observations are evident: There indeed is clearly different character of field profile near edges of respective cross-sections. This character depends on distance of cross-section plane from nearest coil. While under the coil the edges seem to be raised, as can be seen in fig. 2 and fig. 4, the magnitude at the edges for plane located between the coils in fig. 3 and fig. 5 seems to decrease as approaching to coil radius. However, model indicates (as long as near-$Z = 0$ plane is concerned) a very good agreement with $1/R$ character given by Ampere's law. Moreover, the whole liner is located within the area of $1/R$ character, regardless of choice of toroidal location of modeled poloidal cross-section plane. Thus as long as liner of tokamak GOLEM is concerned, model given by Biot-Savart's law degenerates into first approximation given by Ampere's law.

The viability of a model is given by its correlation to real experimental data. Given the current diagnostic means of tokamak GOLEM, relevance of models was tested by their ability to predict total toroidal flux χ from evolution of current in coils of toroidal field generation. As analysis in previous section showed, there is a good agreement between B_T values calculated from currents in coils and sensors of magnetic field detection (at least in the center of chamber). χ was measured by a single toroidal flux measurement loop of 0.145 m radius, placed virtually underneath one coil of B_T generation. It should be noted that there is a voltage divider implemented between the loop and DAS, thus signal of this sensor has to be multiplied by 2. By integration of signal of this sensor, total toroidal flux χ encircled by its radius is obtained. Comparison of measured evolution of this quantity to evolutions given by aforementioned models (obtained by summation of B_T across area of grid representing area of flux sensor) can be found in fig. 6. Biot-Savart's law model seems to better describe measured values. The reason of such a small difference between both models lies in relatively low radius of flux sensor which does not leave much space for difference in models to fully develop. Persisting difference between Biot-Savart's law model and measured quantity might (or might not) be caused by finite toroidal dimensions of B_T coils (which were assumed, unlike their width, to be infinitesimally small in the model) and by uncertainties in exact values radii of coils and flux sensor.

Radial profile of B_T was also measured directly by 3D Hall probe during series of shots. Comparison of measured values to the ones expected by Ampere's law are to be found in

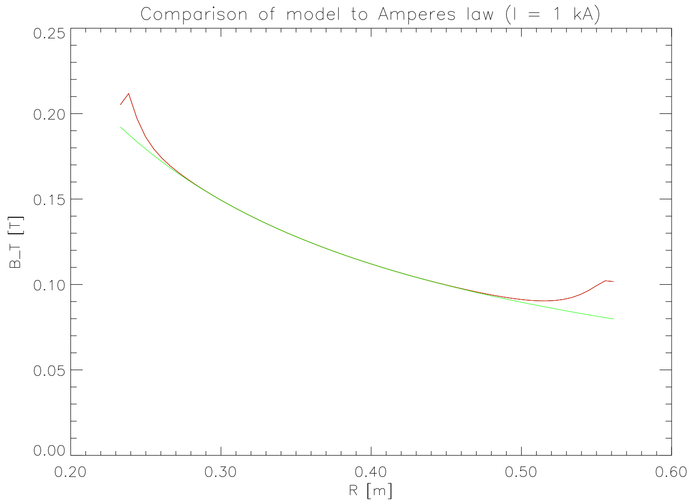

Figure 4: Radial profile of B_T corresponding to $Z = 0$ value of flux sensor location cross-section (red) to model given by Ampere's law (green).

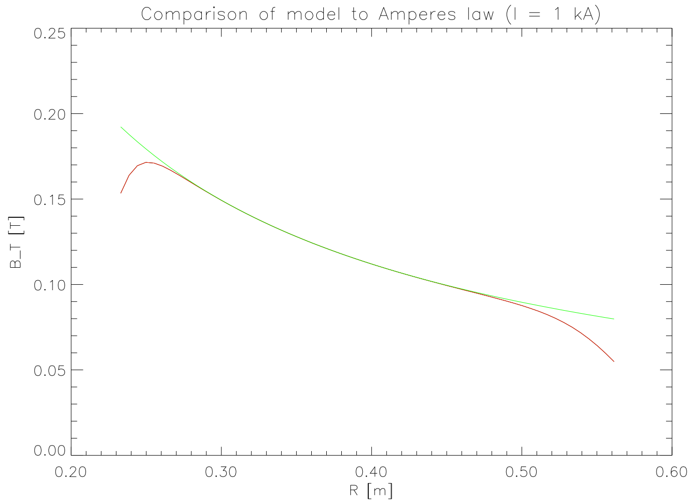

Figure 5: Radial profile of B_T corresponding to $Z = 0$ value of center of large port location cross-section (red) to model given by Ampere's law (green).

fig. 7, where a relatively good agreement between the measured quantity and model can be observed. Since conditions for each shot in the series were slightly different despite our efforts, dimensionless ratio of maximal values in fig. 8 yields more relevant information on actual profile of B_T. Indeed, fig. 8 exhibits deviations from $1/R$ profile at the edges of chamber of the same character as prediction in fig. 5. However, observed deviations are larger than expected. On HFS, observed hall/ampere deviation of 94,77 % appears much closer to the center of chamber, since deviation of 99.73 % was expected. Likewise on LFS, observed deviation of 97.85 % is larger than expected one of 99.95 %. These observations together with difference observed in fig. 6 could imply that B_T ripples on tokamak GOLEM could be much higher than predicted.

4 Passive Stabilization Field Analysis

Thanks to presence of 3-D Hall probe in the center of liner, a preliminary analysis of field of passive stabilization (e.g. the one used to compensate hoop force acting on plasma column) was possible to conduct. By measurement of currents present in stabilization windings, spatial distribution of the windings and use of Biot-Savart's law, reference model for measured values of vertical stabilization field (measured by Hall probe) was obtained. As can be seen in fig. 9, measured values are slightly lower than values given by model, implying possible shielding of stabilization field. This difference proved to be constant for the whole series of shots and equal to hall/model = (85.81 ± 0.37) %. A more detailed experiment would be necessary to provide further insight into this phenomenon.

5 Preliminary Analysis of Hysteresis Curve

In an early tokamak experiments, iron core of transformer enabled to confine magnetic flux from current drive coils within its volume and to reach initially higher toroidal currents. However, at the same time, eventual magnetic saturation of the core resulted in an inductive character of these experiments. On tokamak CASTOR, this saturation value was determined to be equal to 0.16 Vs. By measurement of current in its coils of current drive and integration of its loop voltage during vacuum shot, it is possible to draw hysteresis curve for tokamak GOLEM as well. Results can be observed in fig. 10. According to CASTOR experience, for such a current maximal value of flux, being equal to 0.16 Vs should have been already reached. Fig. 10 thus implies that transformer core has either lost part of its ferromagnetic properties or, which is more likely, this difference might be caused by different (e.g. parallel) implementation of current drive capacitor battery. This phenomenon will most likely undergo more indepth analysis in the near future.

6 Current Sensor Analysis

In this experimental session it was necessary to monitor currents in coils, which was carried out by three different sensors: CLSM-2000 closed loop Hall effect sensor, i6000s Flex AC current probe (further to be referred to as 'Rogowski coil') and i1010 current clamp sensor (referred to as clamp ammeter). In the whole experimental session, normal sensor (e.g. the one with highest reliability) was defined to be CLSM-2000 Hall effect sensor and this is the sensor that provided all the coil current data used in the whole analysis. This section nevertheless provides comparison between outputs of aforementioned sensors with respect to output of normal Hall

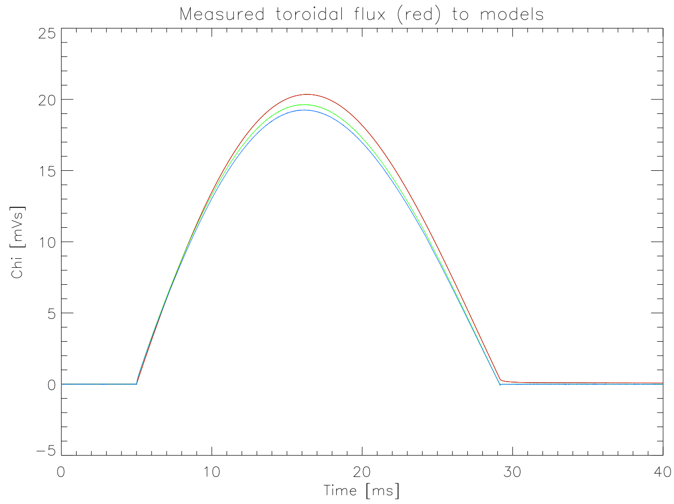

Figure 6: Comparison of χ measured by toroidal flux sensor (red) to Biot-Savart's law model (green) and Ampere's law model (blue).

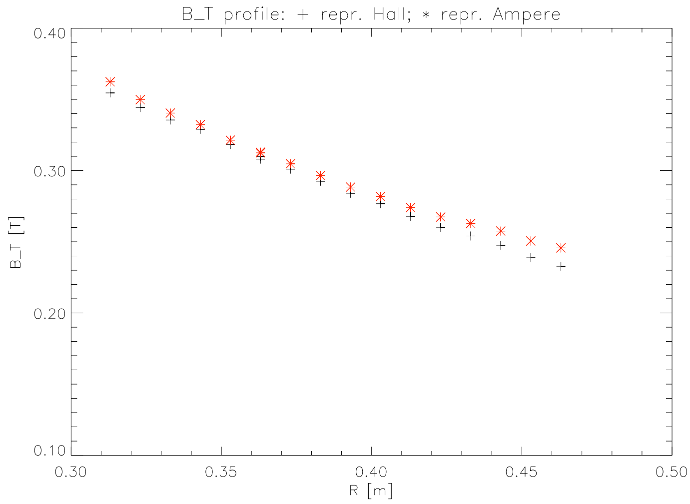

Figure 7: Radial profile of B_T measured by means of Hall probe to Ampere's law values.

sensor.

In fig. 11 a serious disagreement between normal Hall sensor and clamp ampermeter can be observed. Even though the sensor was used within operating range with respect both to current and frequency (though on its upper edge), zero value set accordingly and its calibration constant (1000 A/V) used properly, output of the clamp ampermeter is 2.633 times lower than Hall sensor curve. In contrary, a very good agreement between i6000s and CLSM-2000 outputs is evident in fig. 12. This fact even more points out the possibility of clamp ampermeter malfunction. The cause was not identified, but there is a possibility of damage due to crossing of current operating parameters in the past as 600 A is value easily to be overcome for current drive capacitor discharge.

On slow discharges with relative low current, such as the one in fig. 12, a good agreement between CLSM-2000 and i6000s sensors is observed. Fig. 13 however implies that for high AC currents, i6000s sensor (Rogowski coil) introduces negative offset into the end of measured evolution. The possible cause might lie in inductive character of the sensor e.g. measurement of rate of change of current instead of current itself (analogue integration is carried out by support electronics). Values near maximum of discharge, where the disagreement between non-inductive Hall probe and inductive Rogowski coil starts, are represented on Rogowski coil as near-zero derivation and hence near-zero signal on sensing element. Low sensitivity of sensor (set to 6000 A currents) to such a low values could then result in observed offset.

Absolute value of this observed offset proved to be constant for all the measured currents during the session, being (12.3 ± 0.1) % of maximal measured value in the given discharge. By assumption that the cause of the offset is evenly distributed along the duration of discharge, it is straightforward to eliminate this observed phenomenon. Resulting output of i6000s sensor will hence be of 3.3 % higher magnitude than normal sensor CLSM-2000. This difference, likewise aforementioned offset, proved to be constant for all the used currents and thus by multiplication of i6000s output by 0.967 ± 0.006, output normalized to CLSM-2000 is obtained, as can be seen in fig. 14.

7 Summary

Small coil located on LFS and used for central B_T measurements was finally successfully calibrated. Resulting calibration constant is equal to (70.42 ± 0.90) T/Vs. It is advised constant currently used in analytical algorithms and equal to 87 T/Vs is replaced as soon possible. Calibration also showed that in the center of chamber, there is a very good agreement between B_T measured by Hall probe and values obtained by straightforward use of Ampere's law. Analysis of currents in coils of B_T generation is thus equivalently reliable mean of central B_T determination.

Measurements of B_T field enabled to compare reliability of two possible models of its cross-sectional profile. It was shown that model based on Biot-Savart's law gives a little more accurate predictions of total toroidal flux χ (it should be noted that by analysis of measured values a hidden 1/2 voltage divider on the flux sensor was discovered). Nevertheless, as far as liner is concerned, this more accurate model degenerates into $1/R$ model given by Ampere's law. However, measurements imply that at the edges of liner, deviations from $1/R$ profile occur. Character of these deviations corresponds to the Biot-Savart's law model (although of larger magnitude than expected) and might indicate presence of stronger B_T ripple than expected from theoretical model.

Moreover, experimental setup of session enabled to make preliminary analysis of vertical stabilization field and hysteresis curve. It seems that vertical field of passive plasma position stabilization in the center of chamber is of smaller magnitude than it is expected from model given by currents in the stabilization windings. According to previous experience with maximal flux value of transformer core, smaller

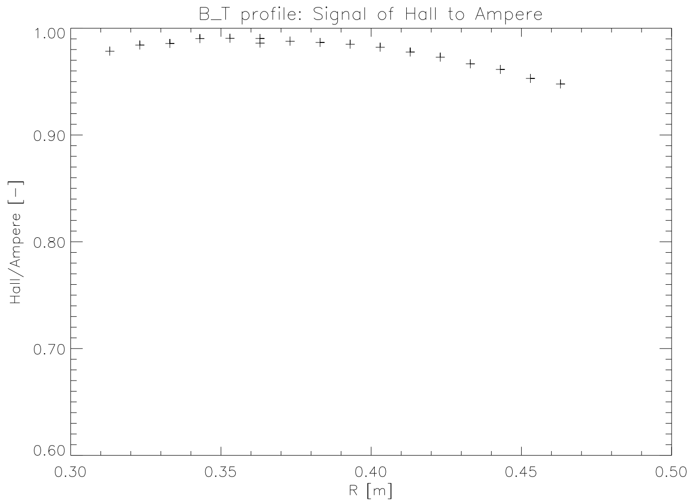

Figure 8: Radial profile of ratio of hall probe signal to Ampere's law prediction.

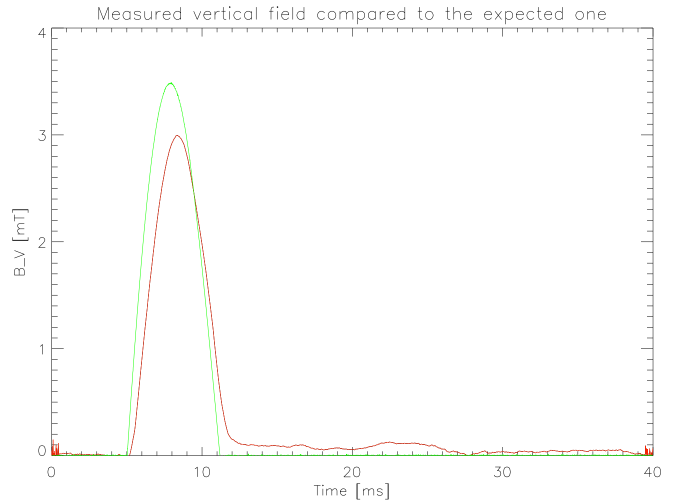

Figure 9: Comparison of measured quantity of vertical field of passive stabilization (red) to model based on currents in coils (green).

fluxes for given currents in primary winding are reached than before. The reason for this will most probably be further investigated in the future.

Finally, series of data obtained in this session enabled to compare reliability of current sensors used on tokamak GOLEM. It was shown that current clamp sensor does not agree with the Hall effect and Rogowski coil based one (which, on the other hand correspond to each other well). When current in coils of toroidal field generation is concerned, it seems that Rogowski coil sensor experiences some difficulties in discharge evolution reproduction, nevertheless a calibration of this sensor to more reliable Hall effect based sensor is provided.

In following sessions, hysteresis of transformer core will probably be investigated more in-depth. Additionally further measurements using 3-D Hall probe magnetic sensor are planned, concerning radial field around ports of chamber and B_T magnitude drop at radius of B_T generation coils.

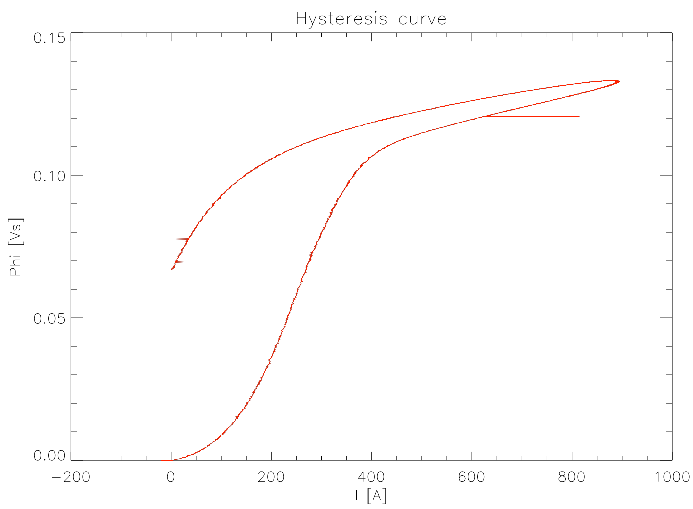

Figure 10: Measured beginning of hysteresis curve of GOLEM transformer.

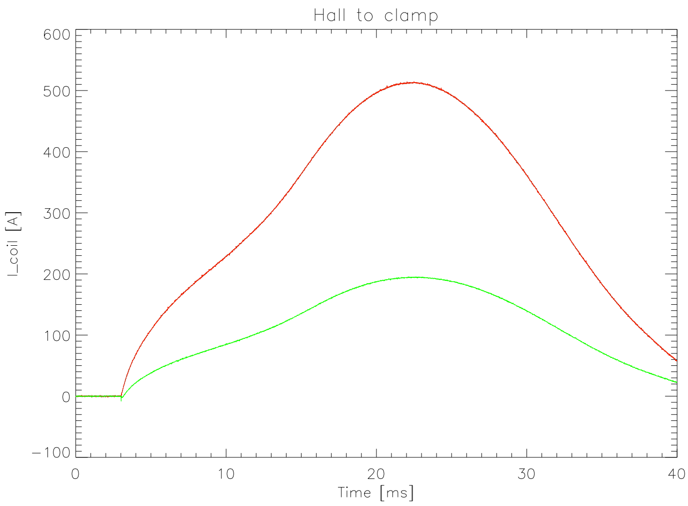

Figure 11: Output of Hall effect current sensor (red) to clamp ampermeter output (green).

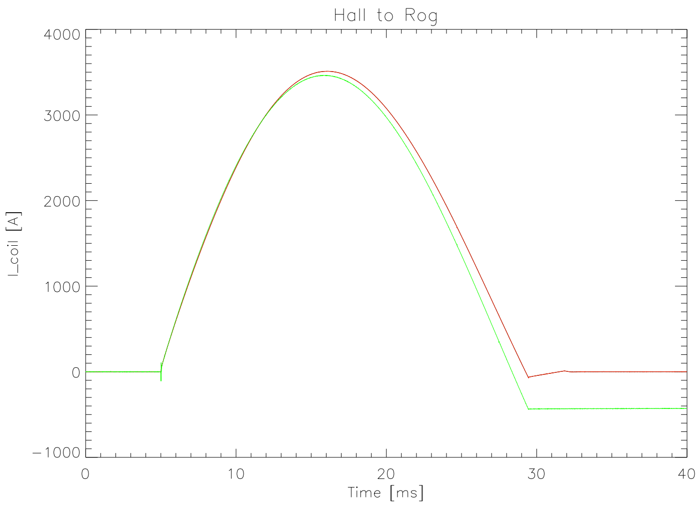

Figure 13: Output of Hall effect current sensor (red) to Rogowski coil output (green).

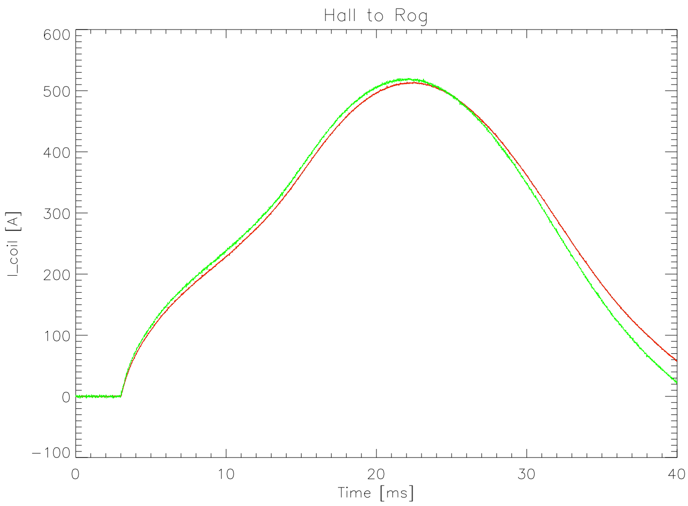

Figure 12: Output of Hall effect current sensor (red) to Rogowski coil output (green).

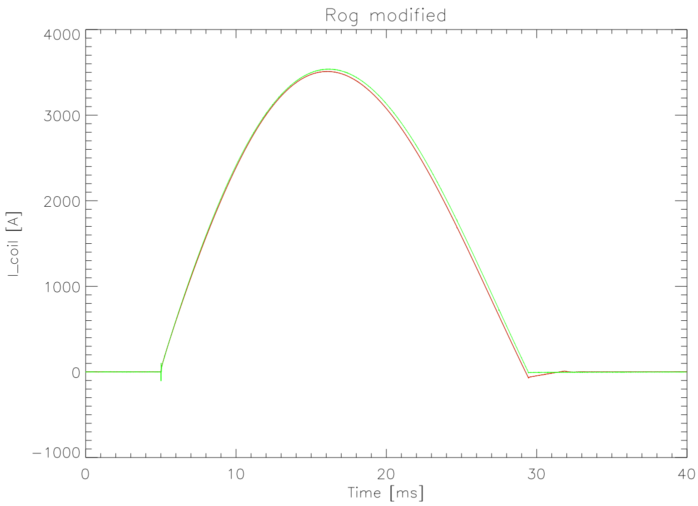

Figure 14: Output of Hall effect current sensor (red) to modified Rogowski coil output (green).