

SIMULATION AND ANALYSIS OF EDDY CURRENT INDUCED IN GLOBUS-M TOKAMAK

ABSTRACT

The paper briefly describes main results of the numerical simulation and analysis of transient electromagnetic processes for plasma discharge scenario # 3106 in the GLOBUS-M tokamak (Ioffe Physical-Technical Institute, Russia). The developed 2-D plasma model uses a parametric representation of the plasma boundary assuming the parabolic distribution of the current density over the plasma cross section.

Keywords: GLOBUS-M spherical tokamak, plasma discharge, eddy currents

I INTRODUCTION

Variation of the magnetic fields in tokamaks during operation induces eddy currents in their conductive structures and results in some energy losses. This paper presents main results of the numerical simulation and analysis of transient electromagnetic processes in the GLOBUS-M tokamak. Eddy current behavior was modeled for a proposed plasma current scenario using measured variations of the coil currents and plasma current, shape and position. The plasma model uses a current loop representation. The plasma shape and current are estimated via plasma boundary parameterization assuming a parabolic current density distribution. Validity of modeling was proved by a comparison of the calculated eddy currents with experimental results on GLOBUS-M. Some principal experimental and theoretical results of the

spherical tokamak plasma investigation and features of the GLOBUS-M tokamak construction and operation are reviewed in [1, 2].

II CALCULATION MODEL

The eddy current analysis was performed with the use of 3D finite-element code TYPHOON [3,4] developed at the Efremov Institute. TYPHOON allows a transient electromagnetic analysis using a finite-element (FE) representation of thin shell structures in an integral formulation to model arbitrary conducting walls of complex geometry. A numerical simulation of the eddy currents requires a reasonably detailed model of the conducting structures.

A finite-element model of the GLOBUS-M tokamak is developed so that to reflect details of the actual design (Figs.1-3). The model includes the vacuum vessel (VV), plasma, 3 pairs of correction coils (CC) used to suppress stray fields, the central solenoid (CS) and 3 sets of field-shaping coils (poloidal field (PFC), vertical field (VFC) and horizontal field (HFC) coils) to confine the plasma. The effect of current variations in the toroidal field coil was ignored because associated eddy currents are not closed in the toroidal direction and give no contribution to the total eddy current in the vacuum vessel. For magnetic diagnostics the Rogowski coils are placed in the plane $\varphi = 270^\circ$ of the GLOBUS-M vacuum vessel.

The vacuum vessel is formed by a 2 mm thick inner cylinder, two 3 mm thick half-spheres and a 14 mm thick outer ring with the equatorial ports as shown in Fig.2. The square equatorial ports have 6mm thick walls. The walls of both large and small round equatorial ports are 3 mm thick. The equatorial port plugs have respective thickness of 11 mm, 10 mm and 6 mm. The half-spheres have

vertical ports of different configurations with 3 mm thick walls. All vertical port plugs are 4 mm thick.

The vacuum vessel is made of stainless steel with the resistivity of $5.7 \cdot 10^{-7}$ Ohm·m. During plasma discharge the vacuum vessel is assumed to be at the room temperature (20°C).

The vacuum vessel is modeled as a single-layer conducting shell. The inputs for modeling field sources were taken from observations in GLOBUS M performed in the Ioffe Physical-Technical Institute (Russia) for plasma discharge scenario # 3106 [5]. The modeling is based on the following assumptions:

- (i) the positive direction of the toroidal plasma current is anticlockwise if viewed from above the vertical axis;
- (ii) the global coordinate system is taken as Cartesian coordinates (X, Y, Z) with the origin at the VV center. The Z axis is vertical, the X axis is directed radially via the center of equatorial port # 1 (ref. Fig.1), the Y axis forms a right-hand system with the other axes as shown in Fig.4.

As seen from Fig.5, the ramp-up phase takes about 27 ms until the plasma current peaks to 356.58 kA at 143ms. As follows from experience, in all cases of monotonically increasing (decreasing) pulse magnetic fields the characteristic depth of a field penetration into a conducting structure has only a weak dependence on a pulse form. Here the characteristic time τ of magnetic field penetration through conducting shell with thickness h and specific electrical resistivity ρ can be estimated as:

$$\tau \approx \frac{\mu_0 h^2}{\rho} \quad (1)$$

Where $\mu_0 = 4\pi \times 10^{-7} \text{ Hm}^{-1}$ is the vacuum permeability. In this case, the phase of electromagnetic process for time $t \gg \tau$ can be precisely described via a thin-shell approximation.

For the GLOBUS-M shell with a maximum thickness of 14mm and a specific electrical resistivity of $5.7 \times 10^{-7} \Omega m$ we shall obtain a characteristic time $\tau \approx 0.43 \text{ ms}$ in accordance with equation (1). Thus, the characteristic time τ of magnetic field penetration through the GLOBUS-M vacuum vessel shell is equal to 0.43ms, which is substantially smaller than the plasma current ramp-up phase of 27ms. Calculations of induced eddy currents due to plasma disruption in the vacuum vessel of the TEXTOR tokamak [*] have been carried out. The mechanical force distribution in space and time has been also calculated. The model of thin shells was used to describe the vacuum vessel. The ports in the vacuum vessel, non-uniformity of the specific electrical resistivity and symmetry of the construction properties are taken into account. The characteristic

III PLASMA CURRENT MODELING

Evolution of the plasma current, shape and position is modeled using approximated results from observations on GLOBUS-M. The plasma model uses a parametric representation of the plasma boundary. A parabolic distribution of the current density is assumed over the plasma cross section.

The plasma boundary is described as:

$$\begin{aligned} R_{pl} &= R_0 + a \cdot \cos(\alpha' + \delta \cdot \sin(\alpha')) \\ Z_{pl} &= a \cdot k \cdot \sin(\alpha'), \end{aligned} \tag{2}$$

where (R_{pl}, Z_{pl}) are the coordinates of a point at the plasma boundary. The time-dependent parameters R_0, a, k and δ denote the major and minor plasma radii, plasma elongation and triangularity respectively. Input variations of these parameters during the plasma discharge are taken from the experimental results reported by the Ioffe Physical - Technical Institute [5].

A moving local coordinate system (R, Z) has its origin at the point $(R_0, 0)$ corresponding to the magnet axis of a family of magnetic surfaces. A poloidal angle α is assumed positive anticlockwise from the R axis to the axis Z . The poloidal angle is expressed as:

$$\alpha(R, Z) = \text{arctg}\left(\frac{Z}{R - R_0}\right) \quad (3)$$

Eqs.(2) and (3) give a relation between the angle α and parameter α'

$$\cos(\alpha' + \delta \cdot \sin \alpha') - k \cdot \sin \alpha' \cdot \text{ctg} \alpha = 0 \quad (4)$$

A plasma volume Ω is modeled via the evolution of the plasma boundary during discharge. The calculated region is determined in terms of the boundary limits

$$\Omega = [R_{\min}, R_{\max}] \times [Z_{\min}, Z_{\max}]$$

$$\Omega = [0.12\text{m}, 0.61999\text{m}] \times [-0.39999\text{m}, 0.39999\text{m}]$$

The distributed plasma current is modeled by current loops at given points inside the calculated region.

Figure 5 illustrates plasma current evolution from experiments on GLOBUS-M. Within the time interval from 26 ms to 57 ms no plasma current occurs. The plasma current is initiated at 58 ms. For the period 58 ms to 114 ms the plasma current is modeled by a single current loop. After 115 ms the plasma shape and

position start to vary, and the plasma current rapidly increases. The ramp-up phase takes about 27 ms until the plasma current peaks to 356.58 kA at 143 ms. Within the interval from 115 ms to 146 ms the plasma current is modeled with 1440 current loops in order to reflect substantial changes in the plasma shape and position.

Variations of the plasma shape and position for different time points are shown in figure 6. The plasma is limited during the discharge.

The calculated region Ω is divided into $N = 30 \times 48$ elements along the R and Z axes so that to ensure $\Delta r = \Delta z$. The plasma current is then obtained as

$$I_{pl} = \Delta S \sum_{i=1}^N j_i ,$$

where j_i is the plasma current density of the i -th current loop, $\Delta S = \Delta r \cdot \Delta z$ is the area of the current loop cross section, or a mesh finite element.

An equilibrium current density in the plasma cross section corresponds to a non-uniform current distribution and can be interpolated using a parabolic distribution of the form

$$j_i = j_0 \left(1 - \frac{(R_i - R_0)^2 + (Z_i)^2}{(R_{pl} - R_0)^2 + (Z_{pl})^2} \right). \quad (4)$$

Here (R_i, Z_i) are the coordinates of the i -th current loop center, j_0 is the normalization factor dependent on the full plasma current I_{pl} .

In equation 5, central coordinates of the model current loops (R_i, Z_i) and plasma boundaries (R_{pl}, Z_{pl}) are located on a line originated from the point $(R_0, 0)$. To determine the plasma boundary as given in equation (2), a relation

between α and α' should be found. If an angle α_i is given by equation (3), then the respective parameter α' can be found by solving equation (4) using the Newton method. The resulting α' is consistent with the angle α and can be applied to determine the plasma boundary coordinates (R_{pl}, Z_{pl}) . If the calculation model is correct, the current loops uniformly cover the region inside the plasma boundary.

The plasma model has been benchmarked against a geometrical reconstruction of the plasma boundary and allocation of current loops with non-zero current density from equations (2)-(5). The current loop locations are taken as coordinates of their centers. Fig.7(a) shows the geometrical results for an event of the plasma discharge scenario at 143 ms when the largest plasma cross-section occurs. Fig. 7(b) plot isolines of a plasma current density obtained for the same event.

IV PFC CURRENT OBSERVATIONS

The GLOBUS-M poloidal field system includes the poloidal field coils PF1, PF3, correction coils CC1, CC2, CC3, vertical field coil VFC and horizontal field shaping coils HFC1 and HFC2, and two-sectional central solenoid as shown in Fig.3. The correction coils are connected in series. The HF coils are grouped in pairs, the lower ($z < 0$) and upper ($z > 0$) pair being connected electrically in antiserries.

V RESULTS

Numerical simulation of transient electromagnetic processes in the GLOBUS-M vacuum vessel from the plasma discharge observations gives a prediction for the total toroidal eddy currents.

Fig.8 illustrates a comparison between the modelled and measured variations of the toroidal eddy current. The peak eddy currents of 55-56 kA occur at 112 ms, preceding plasma current ramp-up, and are caused by variations in the central solenoid current.

Oscillations of the evolutions of eddy currents are associated with power supplies. The coils are energized with 110 kV ac transformers connected to mains via six-phase thyristor rectifiers. Output ripple is typically 300 Hz.

The study also included an analysis of an impact of the poloidal angle α on the toroidal eddy current density. The toroidal angle was taken as $\sim 270^\circ$ to fit the external and internal sets of Rogowski coils [6]. The poloidal angle was varied in the (R, Z) plane as given in Fig.9.

Fig.10 shows the eddy current density as a function of the poloidal angle for five typical events of the plasma discharge scenario:

1. 30ms – start of the CS current fast growth;
2. 58ms – plasma current initiation;
3. 114ms – end of practically immovable position of plasma;
4. 115ms – start of plasma current ramp-up and variations of the plasma shape and position;
5. 143ms – peak plasma current of 356.6kA.

Figs.11, 12 illustrate distributions of the eddy currents and current surface density of the eddy for few typical events of the plasma discharge scenario.

Simulated variations in the eddy current in main components of the vacuum vessel are shown in Fig.13.

During the period 113 ms to 120 ms, when the eddy current is near maximal, the total eddy current is split so that up to 50%, or 40 kA, pass through the inner cylinder and ~35%, or 25 kA, through half-spheres. The eddy current in the outer ring is practically zero. The plasma current in this period rises from 5 kA to 105 kA. This situation is typical for spherical tokamaks with a short current path around the inner cylinder and, consequently, low ohmic resistance of this cylinder.

The total resistance for the vacuum vessel is estimated in terms of heat load Q due to the toroidal eddy current I using the equation

$$R \int_0^t I^2(t) dt = Q$$

At $\rho=5.7 \cdot 10^{-7} \Omega \cdot m$ the VV resistance in the toroidal direction is $110 \mu \Omega$.

VI CONCLUSIONS

A full-scale numerical model was developed to study eddy current behavior in the vacuum vessel of the GLOBUS-M tokamak. Analysis of transient electromagnetic processes in the conducting structures was performed using the TYPHOON simulations. Eddy current evolution was modeled on the basis of experimental data for the GLOBUS-M plasma discharge scenario. Simulated and measured curves are in a good agreement. The eddy current simulations were applied to investigate a distribution of the toroidal eddy current surface density and evolution of the total eddy currents for the typical events of the plasma discharge scenario. The results showed that the inner cylinder of the

vacuum vessel allocates up to 50% of the total eddy current due to a rather low ohmic resistance in the toroidal direction. The decay time for this cylinder amounts to 0.25-0.3 ms. The vacuum vessel time constant governing a steady-state distribution of eddy currents is evaluated as (2.5-3) ms. The total resistance of the vacuum vessel in the toroidal direction is estimated as $110 \mu \Omega$ at $\rho=5.7 \cdot 10^{-7} \Omega \cdot \text{m}$.

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FIGURE CAPTIONS

Figure 1: GLOBUS-M vacuum vessel (view from above) and related global coordinate system

Figure 2: Conductive components of GLOBUS-M vacuum vessel

Figure 3: GLOBUS-M magnet system

Figure 4: Finite-element calculation model of GLOBUS-M vacuum vessel

Figure 5: Measured plasma current

Figure 6: Variations of the plasma shape and position during plasma discharge:

1- 115ms, 2-116ms, 3-117ms, 4-124ms, 5-131ms, 6-143ms, 7-145ms.

Figure 7

a) Geometric plasma boundary and allocation of model current loops at 143ms. Peak plasma current of 356.6kA, largest plasma cross section

b) Isolines of current density over plasma cross section at 143ms

Figure 8: Toroidal eddy current in GLOBUS-M vacuum vessel: 1 – experimental results, 2 – simulated results.

Figure 9: Reference point $(R, Z) = (0.3665\text{m}, 0)$ for poloidal angle α relative to VV midplane

Figure 10: Simulated eddy current density vs. poloidal angle for typical events of the plasma discharge scenario: 1-30ms, 2-58ms, 3-143ms, 4-115ms, 5-114ms. Toroidal angle $\varphi \sim 270^\circ$.

Figure 11: Eddy current distribution at the start of the CS current fast growth (30ms). Isoline step – 200A.

Figure 12: Eddy current distribution at peak plasma current of 356.6kA (143ms). Isoline step - 500A.

Figure 13: Simulated variations of the eddy current in main components of GLOBUS-M vacuum vessel: 1 – inner cylinder; 2- half-spheres; 3 – outer ring.

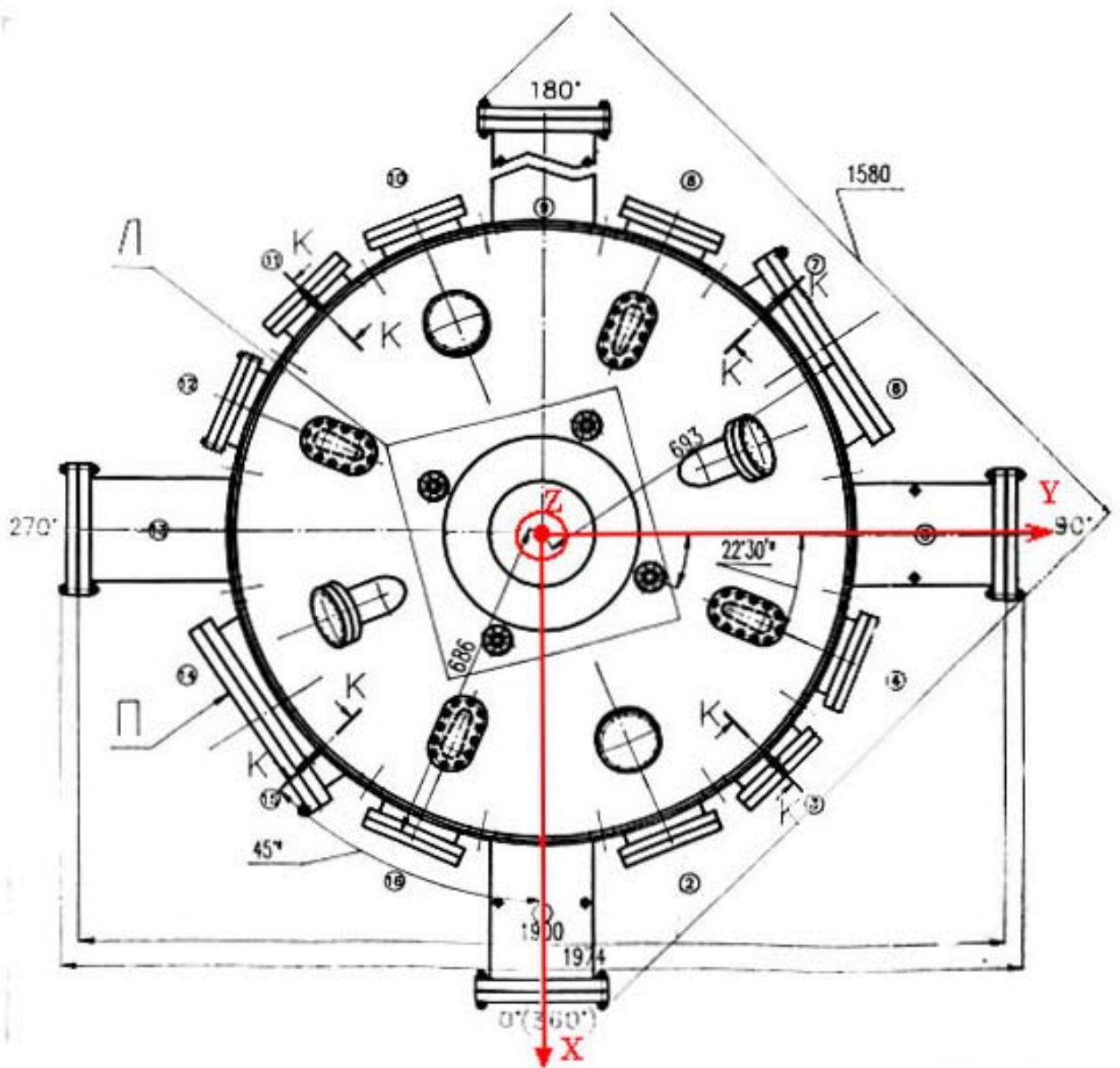


Fig.1 GLOBUS-M vacuum vessel (top view) and related global coordinate system

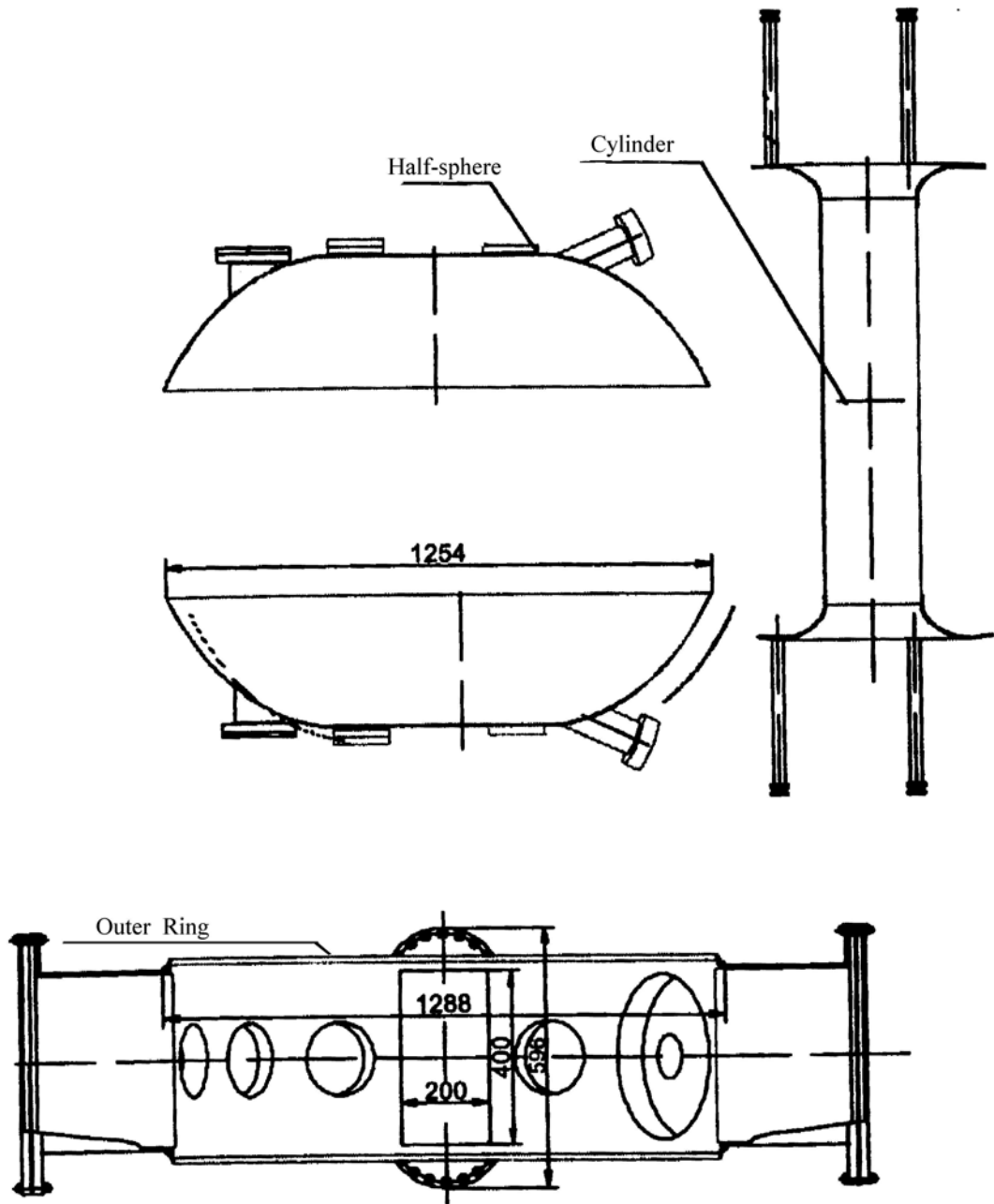


Fig. 2: Conductive components of GLOBUS-M vacuum vessel

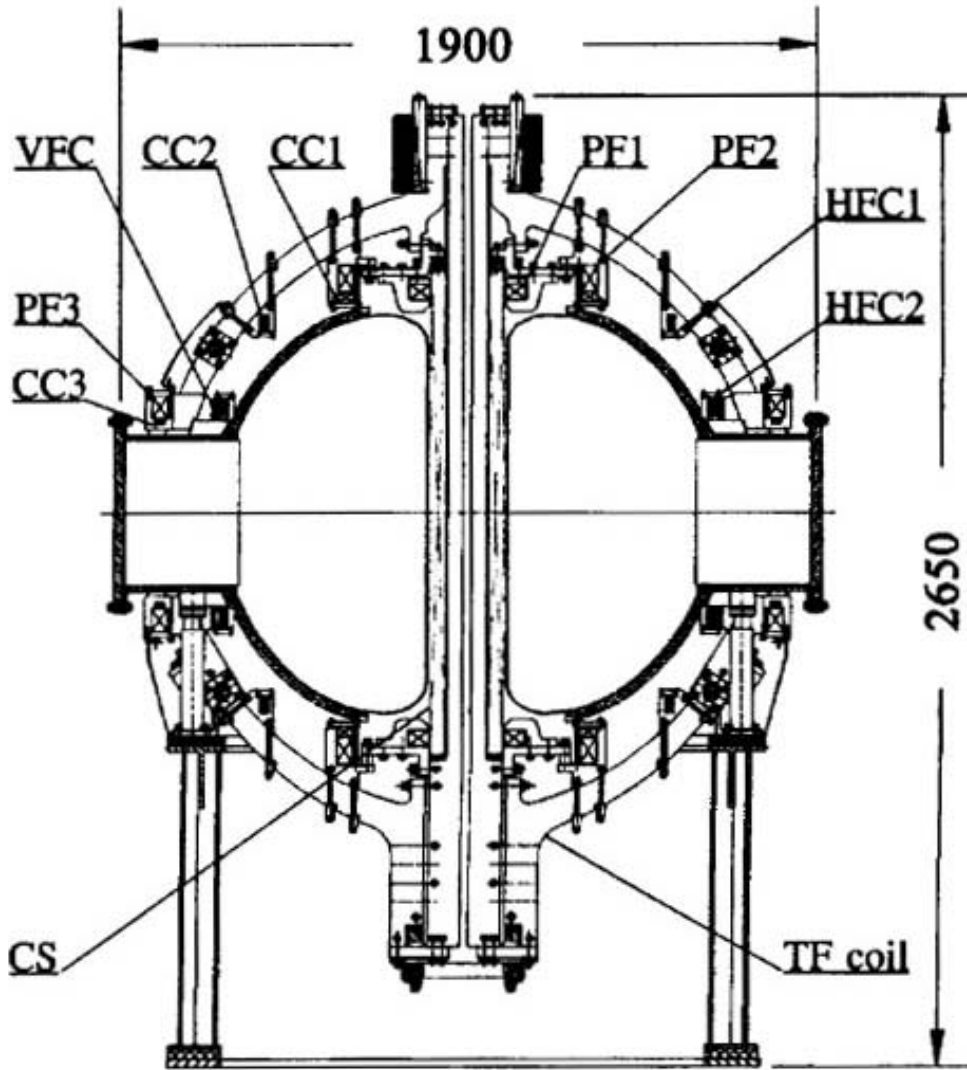


Fig. 3: GLOBUS-M magnet system

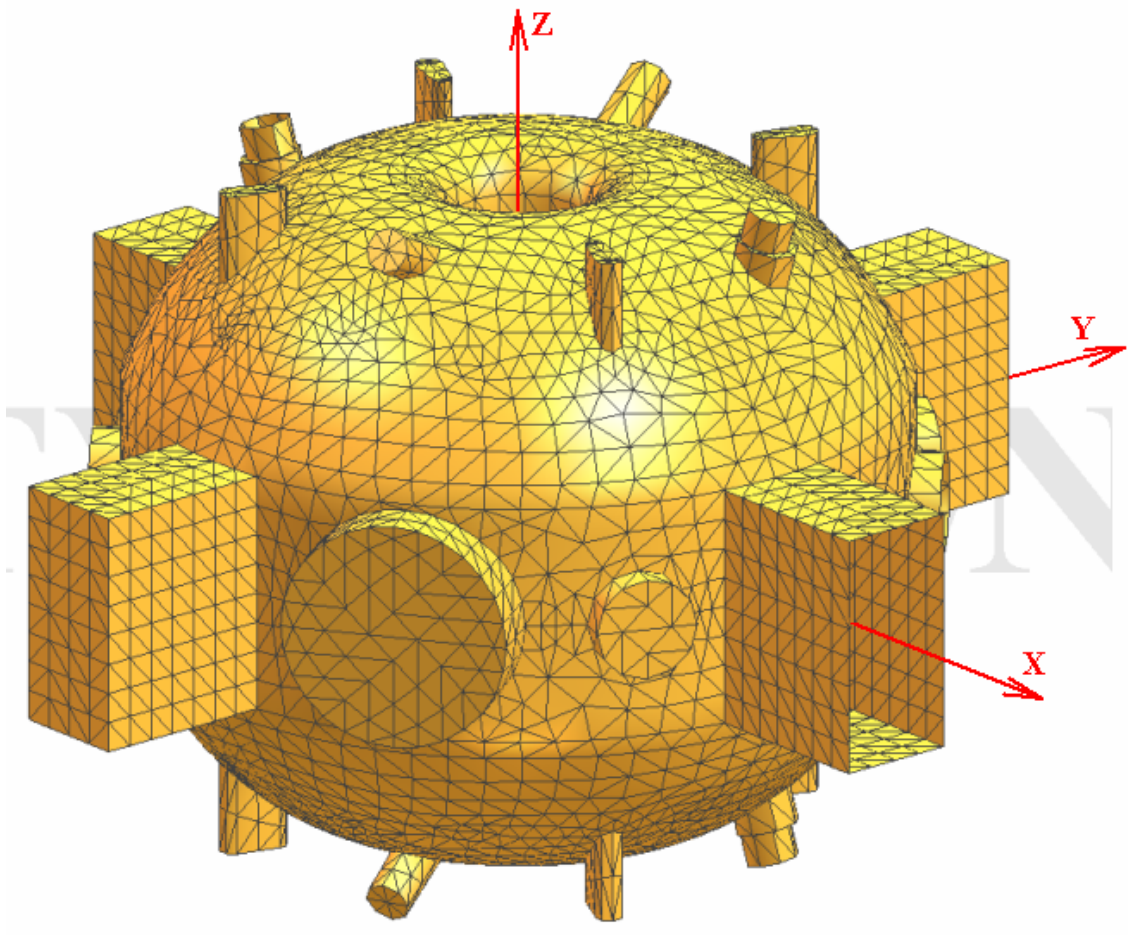


Fig.4: Finite-element calculation model of GLOBUS-M vacuum vessel

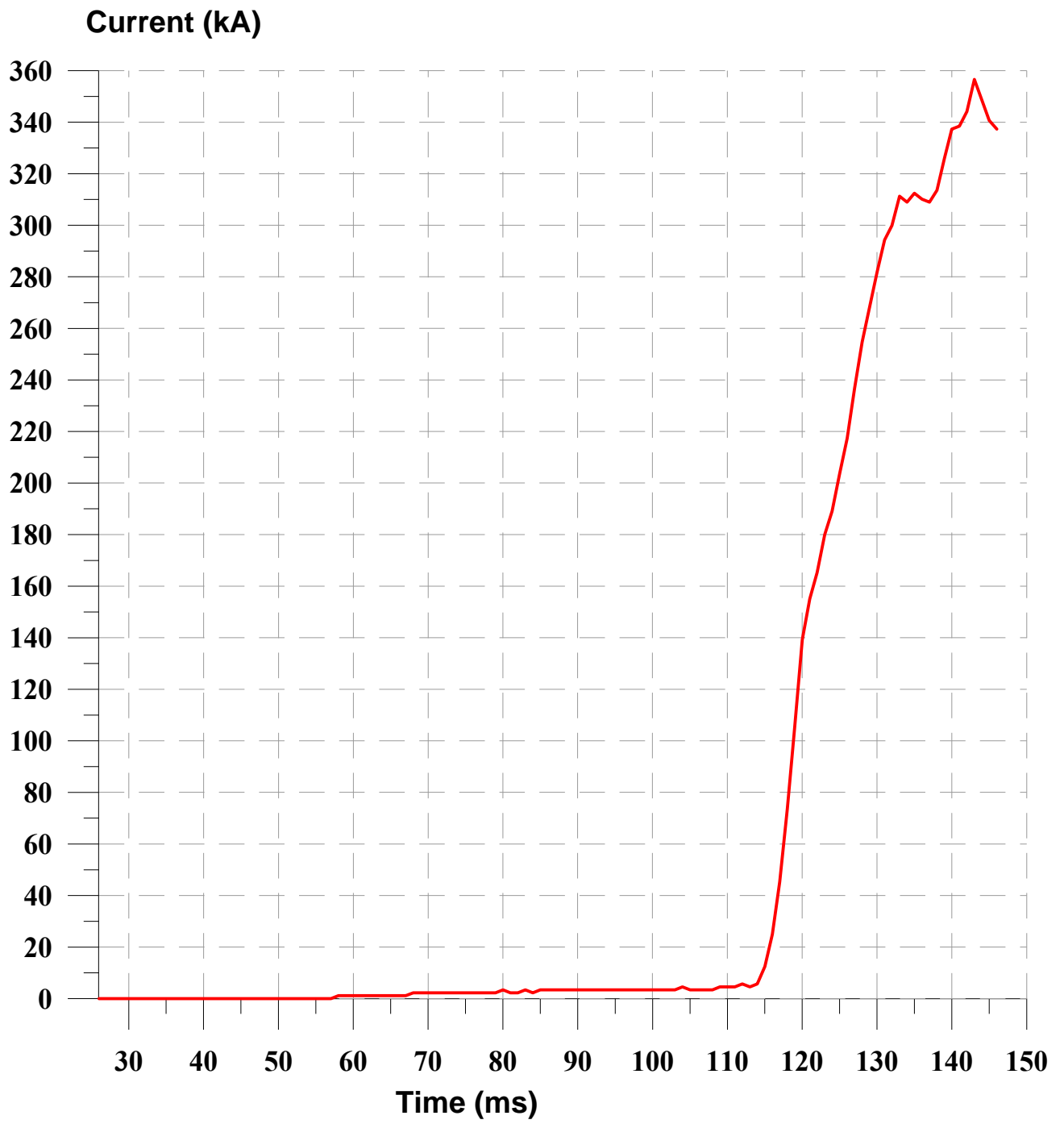


Fig. 5: Measured plasma current

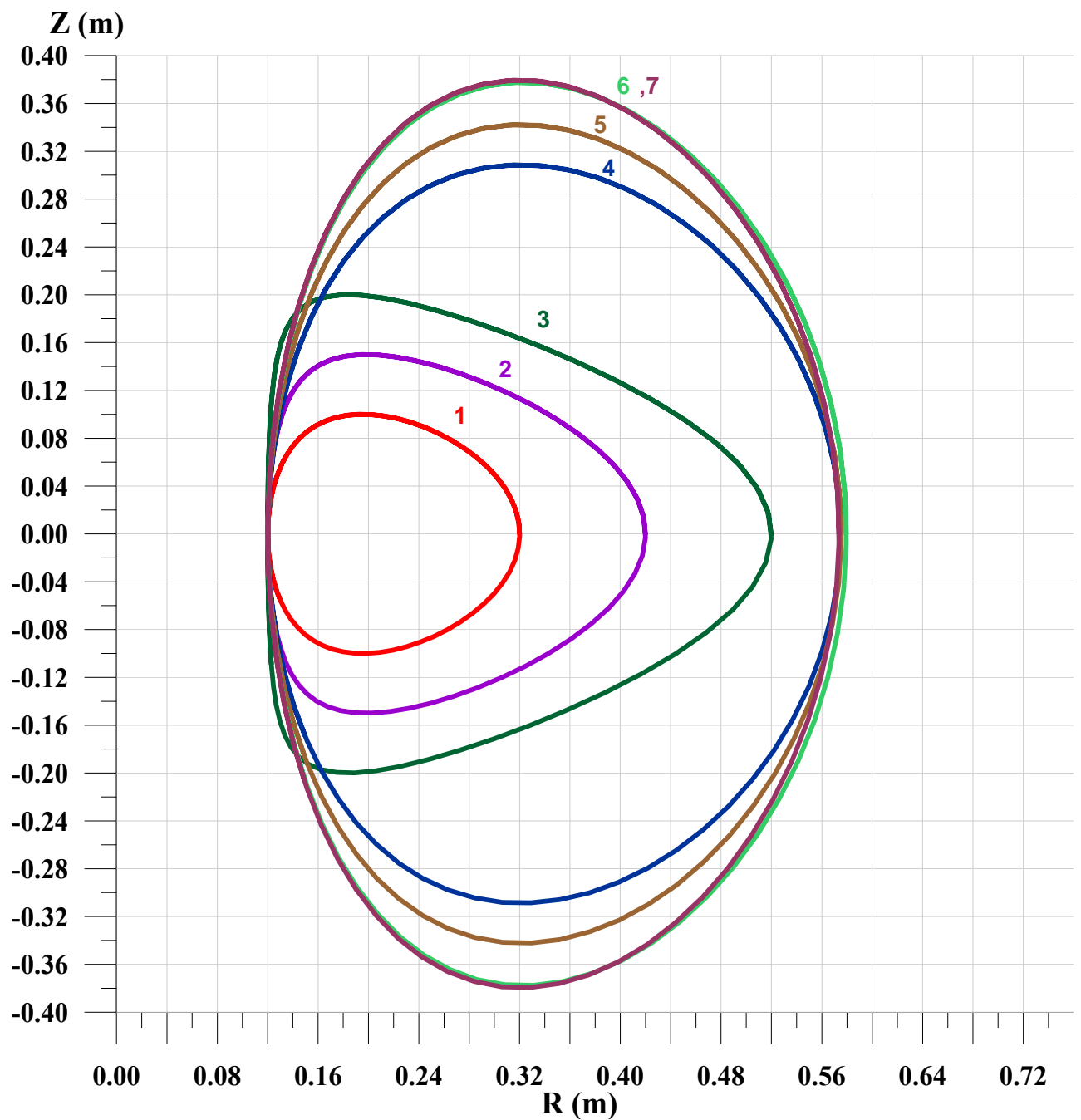


Fig. 6 Variations of the plasma shape and position during plasma discharge: curve1, 115ms; curve 2,116ms; curve 3,117ms; curve 4,124ms; curve 5,131ms; curve 6,143ms; curve 7,145ms.

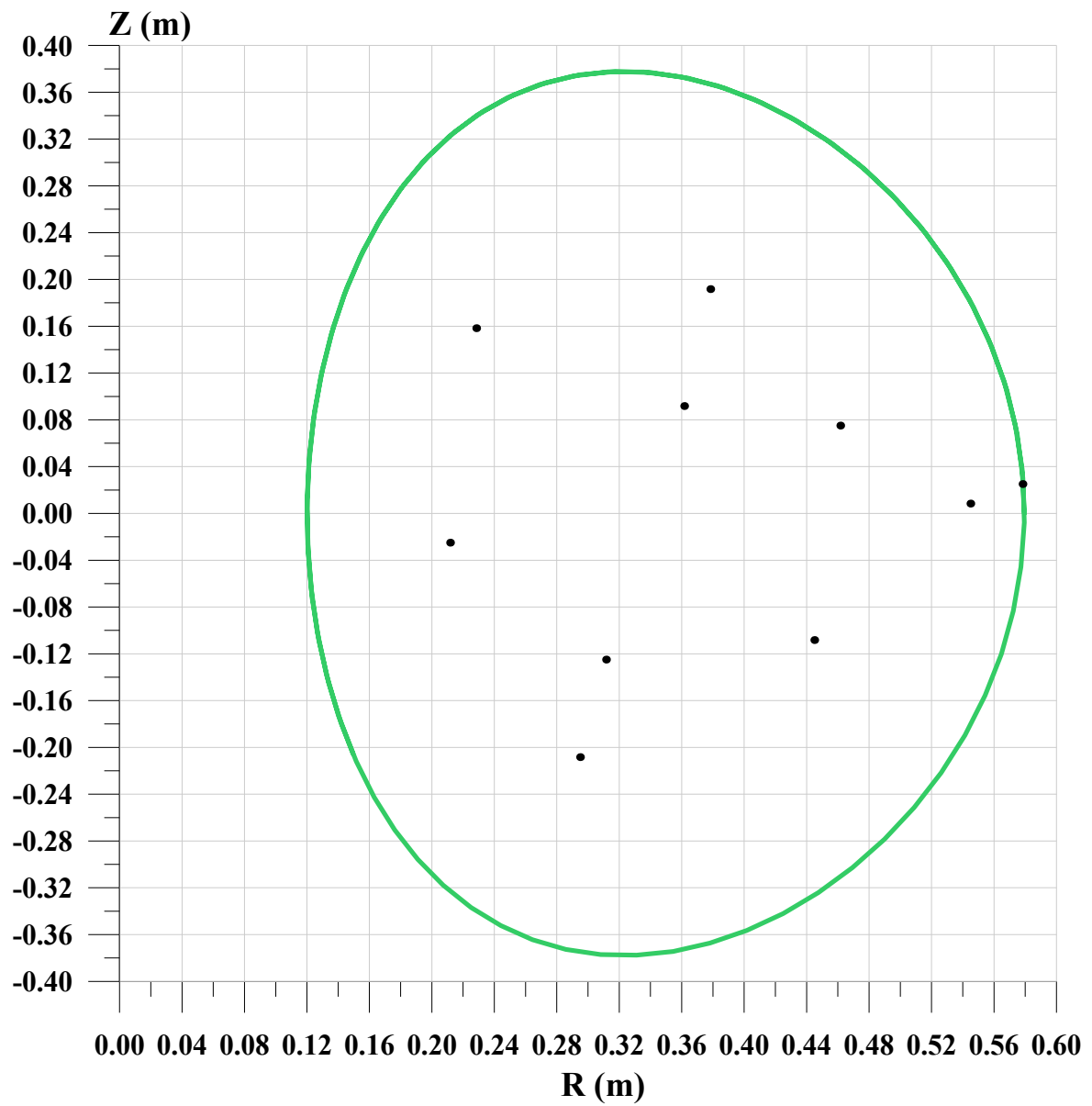


Fig. 7a Geometric plasma boundary and allocation of model current loops at 143 ms, (peak plasma current of 356.6kA; largest plasma cross section).

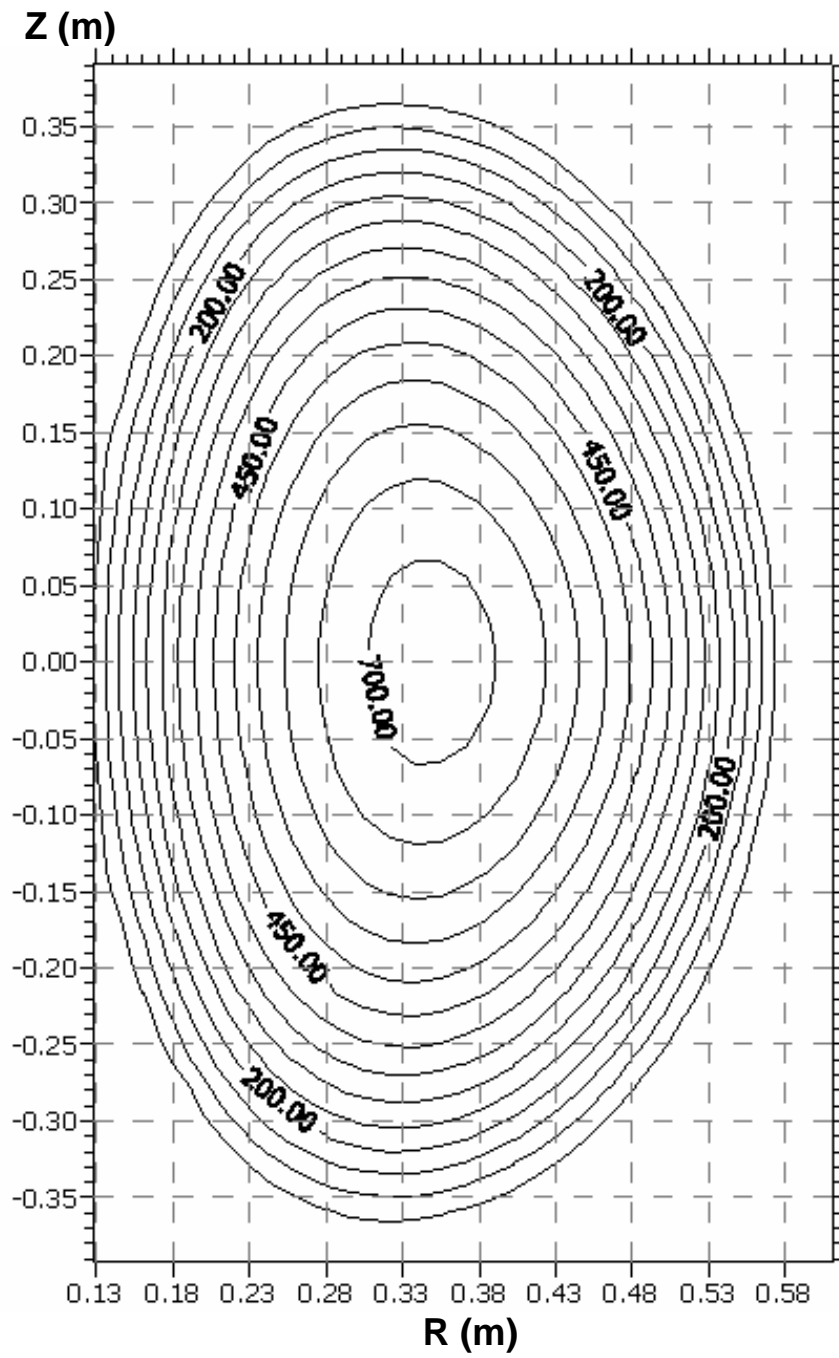


Fig. 7b Isolines of current density over plasma cross-section at 143ms

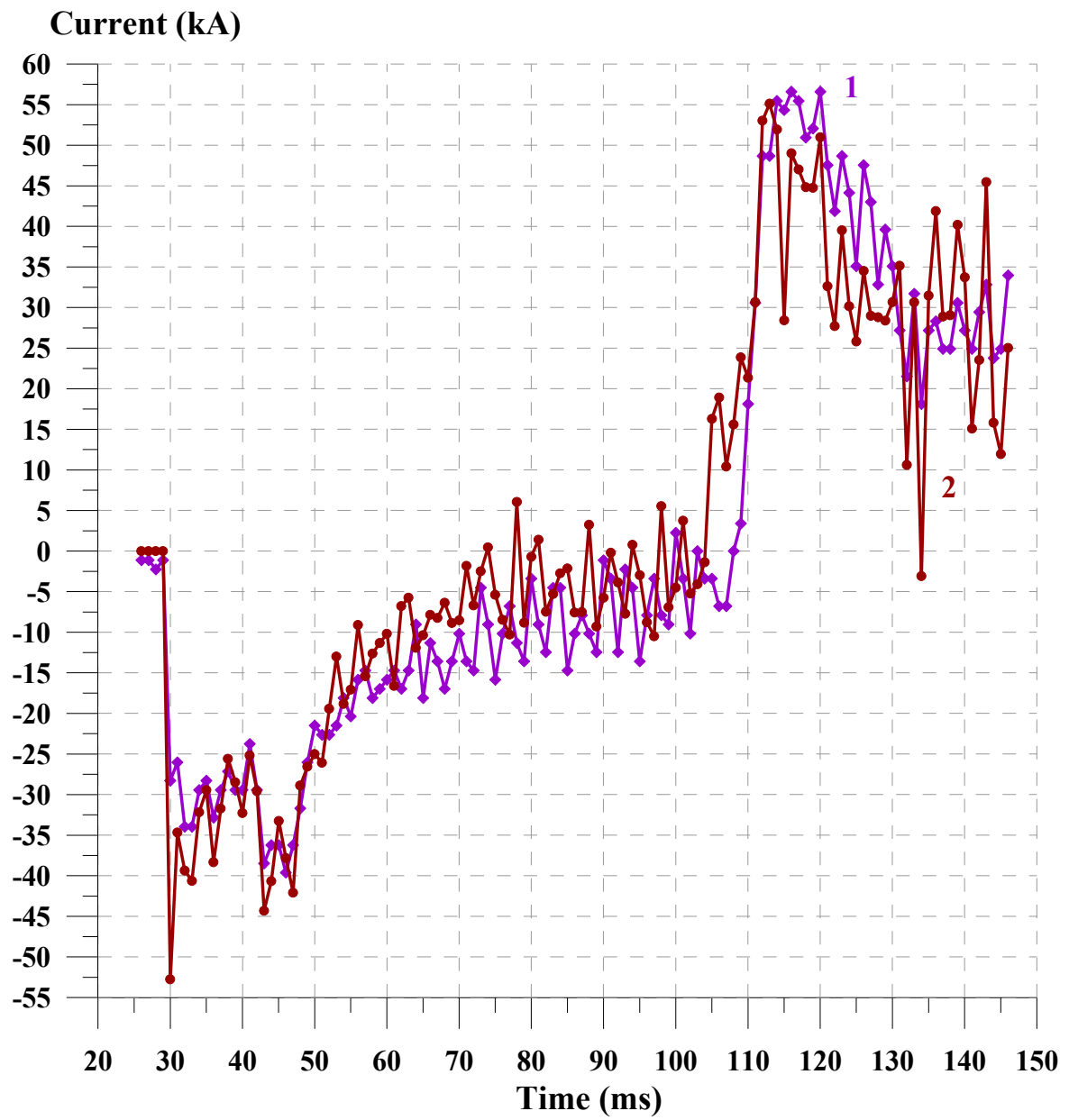


Fig. 8 Toroidal eddy current in GLOBUS-M vacuum vessel: curve 1, experimental results; curve 2, simulated results.

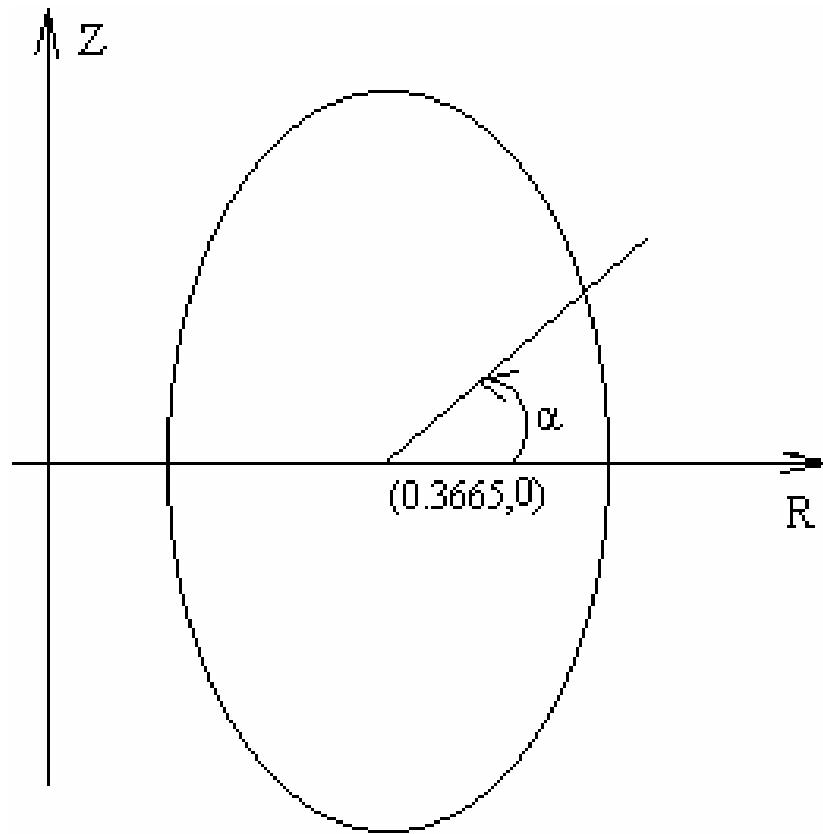


Fig. 9 Reference point $(R, Z) = (0.3665\text{m}, 0)$ for poloidal angle α to the midplane of the vacuum vessel.

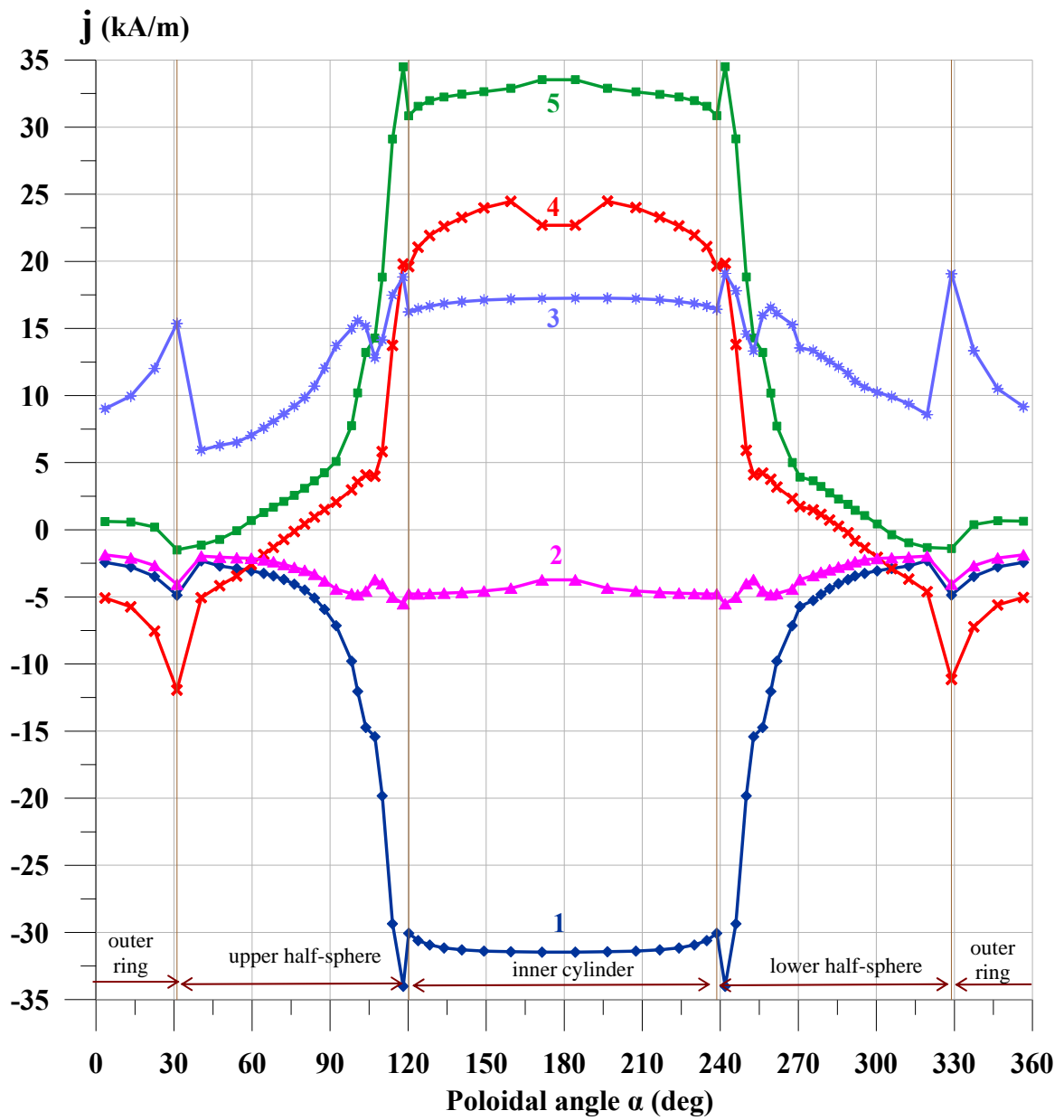


Fig. 10 Simulated eddy current density versus poloidal angle for typical events of the plasma discharge scenario (toroidal angle $\varphi \approx 270^\circ$): curve 1, 30ms; curve 2, 58ms; curve 3, 143ms; curve 4, 115ms; curve 5, 114ms.

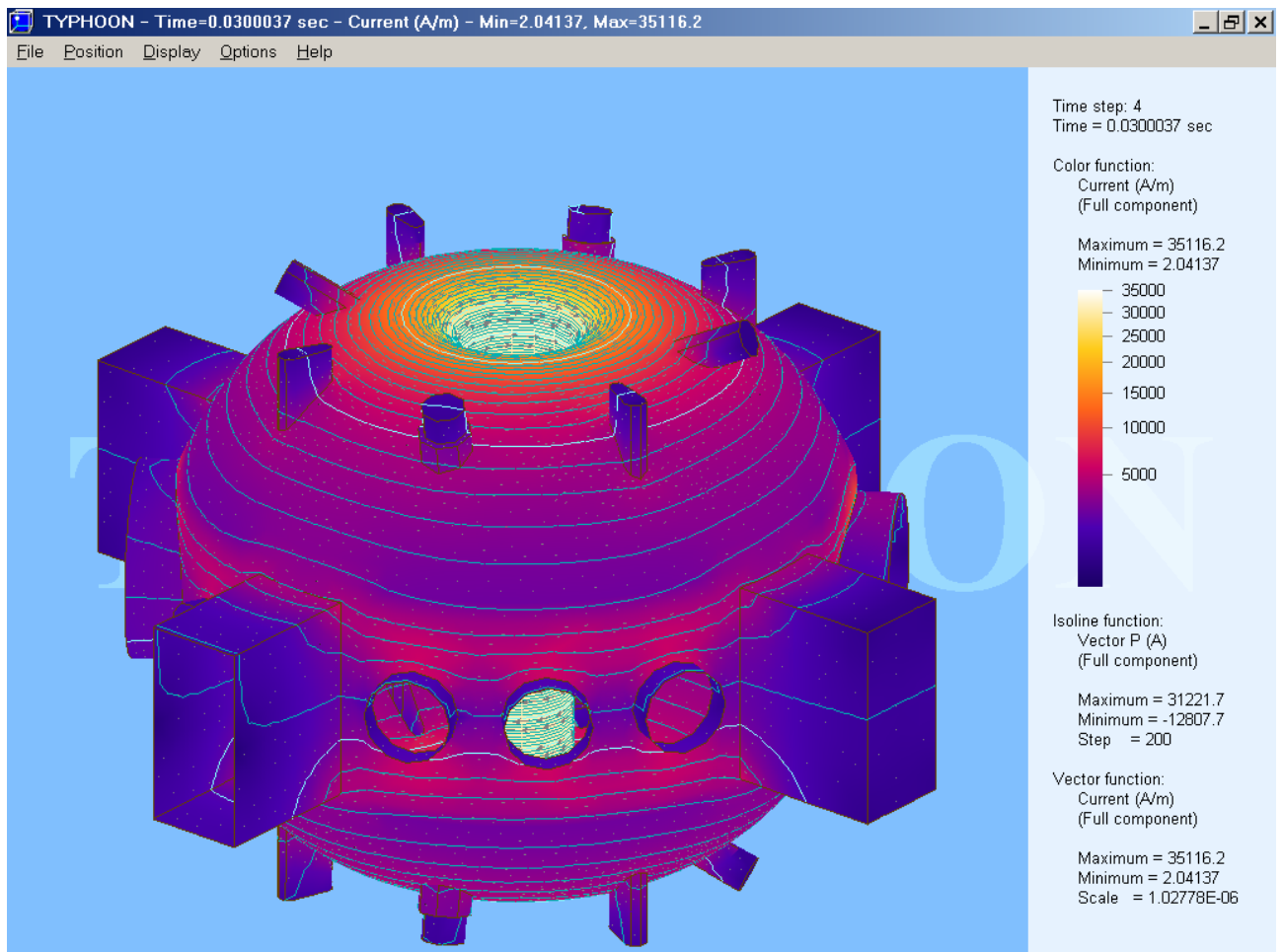


Fig. 11 Distribution of eddy current at the start of the fast growth of the central solenoid current (30ms)(isoline step, 200A)

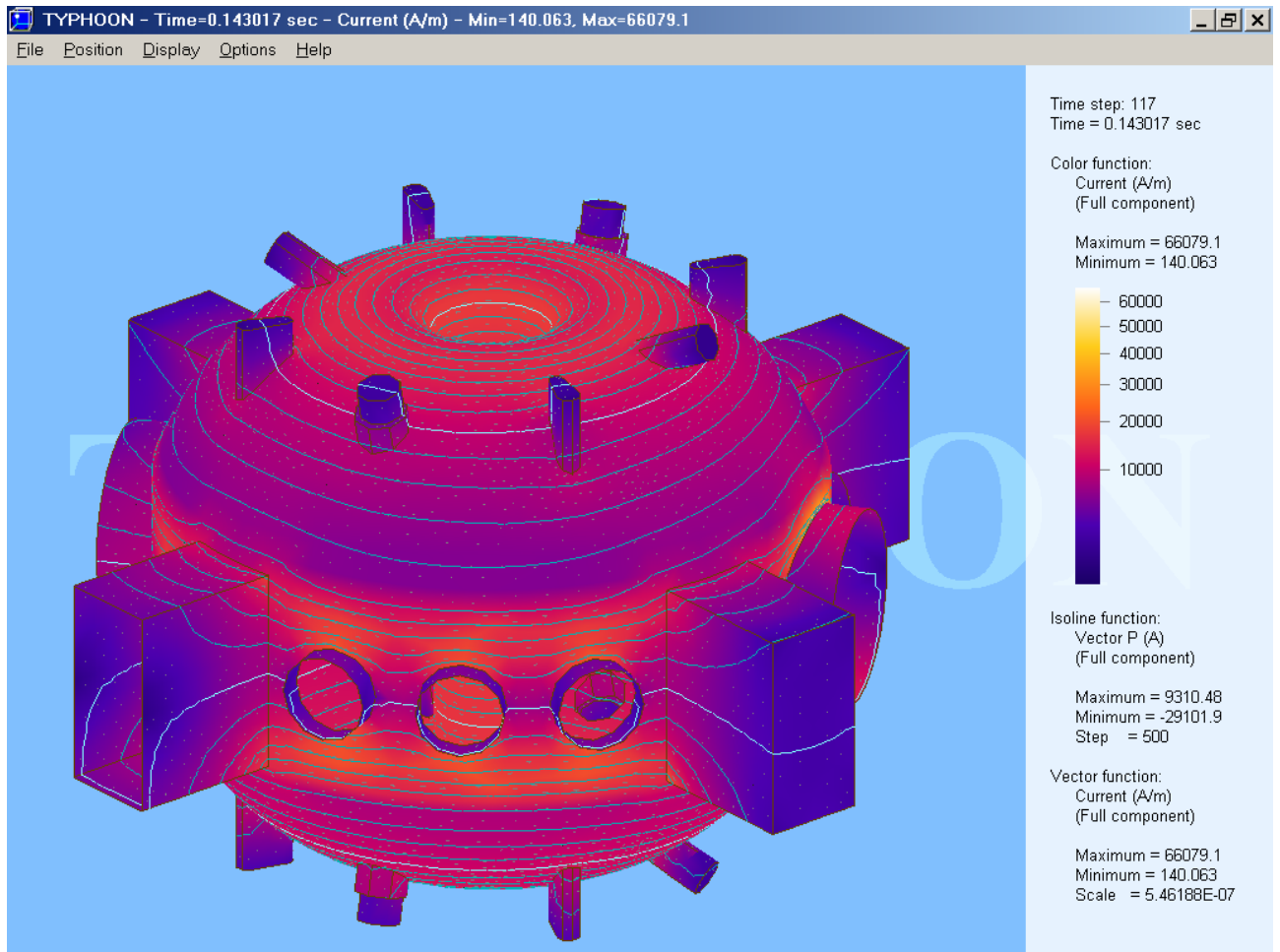


Fig. 12 Distribution of eddy currents at the peak plasma current of 356.6 kA (143ms) (isoline step - 500A)

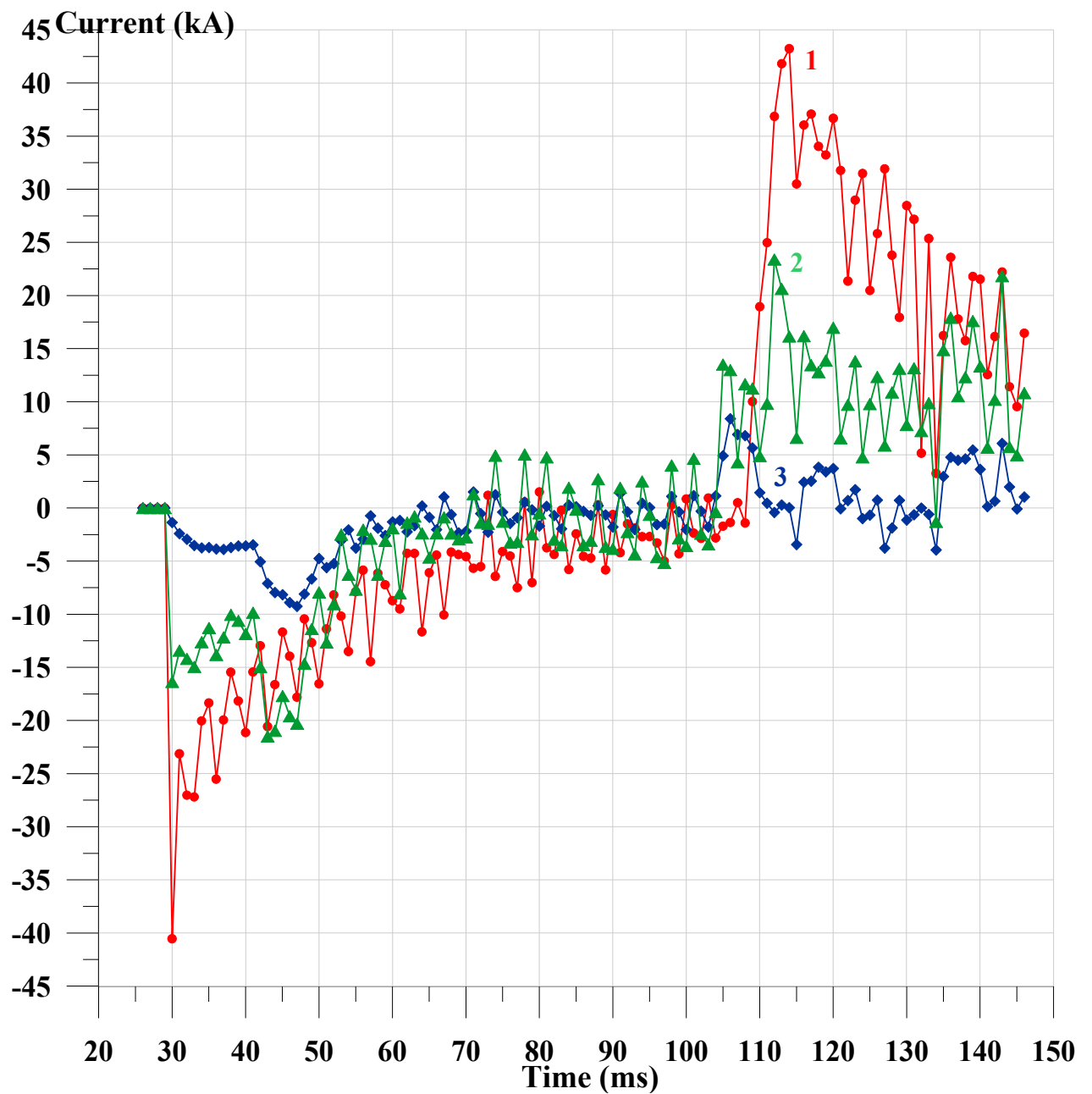


Fig. 13 Simulated variations of the eddy current in main components of GLOBUS-M vacuum vessel: curve 1, inner cylinder; curve 2, half-spheres; curve 3, outer ring.