

Compact toroid challenge experiment with the increasing in the energy input into plasma and the level of trapped magnetic field



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HIGHLIGHTS

- Compact torus formation method with high level of magnetic flux is proposed.
- A compact torus is produced in a theta-pinch-coil with pulse mode of operation.
- Key feature is a pulse of current in an axial direction.
- We report a level of linked magnetic flux is higher than theta-pinch results.

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ABSTRACT

The present work reports on compact toroid hydrogen plasma creation by means of a specially designed discharge system and results of magnetic fields introduction. Experiments in the compact toroid challenge (CTC) device at P.N. Lebedev Physical Institute (FIAN) have been conducted since 2005. The CTC device differs from the conventional theta-pinch formation in the use of an axial current for enhanced efficiency. We have used a novel technique to maximize the flux linked to the plasma. The purpose of this method is to increase the energy input into the plasma and the level of trapped magnetic flux using an additional toroidal magnetic field. A study of compact torus formation with axial and toroidal currents was done and a new method is proposed and implemented.

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1. Introduction

Compact torus (CT), such as spheromak, and field-reversed configuration (FRC) is a so-called alternative fusion scheme [1–5]. CT has several features that make its application promising as a magnetic confinements system: high ratio between plasma pressure and magnetic pressure, therefore, plasma energy in the CT is 70–80% of the total energy. However, there are some problems connected with the non-equilibrium states and quasi-stationary regimes. One of the possible solutions is the pulsed operation, instead of stationary or quasi-stationary.

A compact toroid has an ideal geometry for a fusion reactor [3,6,7], tokamak fueling [8], neutron source [9], magnetized target in magneto-inertial fusion [10–12], fusion propulsion system [13], or liquid blanket configuration [14]. The FRC plasma is

a compact toroid confined by an exclusively poloidal magnetic field. Separatrix, dividing closed and opened field lines is a natural boundary of the hot plasma. Plasma contains particles with non-uniform distribution function – fusion products and components with maxwellian distribution function – background plasma. Fortunately, in compact toroid almost all of the charged particle transport losses will flow out the ends of the device. Therefore, transport from the plasma edge may be reduced by applying an arbitrary system that can change magnetic field shear (perturbing magnetic field is about 1–3% of the main magnetic field). It is very important for tokamak and may be tested on the compact toroids.

Formation of the FRC by using the theta-pinch technology is well established [2,15,16]. CT formation by spheromak merging [17–19], colliding beams [3], a rotating relativistic electron beam [20], rotating magnetic field current drive [21,22], and others [23–25] were studied. Some experiments are now conducted in different countries. In these experiments, plasmas launched by plasma guns implode an FRC or spheromak [26].

One of the main CT formation problems is the low level of the linked magnetic flux. This research provides solution for CT

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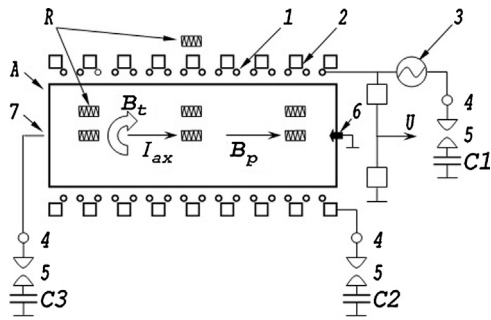


Fig. 1. The general scheme of the CTC experiment: 1 – the main solenoid; 2 – the auxiliary solenoid; 3 – current interrupter; 4 – Rogowski belts; 5 – dischargers; 6, 7 – high-voltage electrodes for the axial current; capacitor banks C1, C2, C3; U is the voltage divider, R is the magnetic probe, A is the vacuum chamber, B_p is the magnetic field of the solenoid, B_t is the toroidal magnetic field, I_{ax} is the axial current.

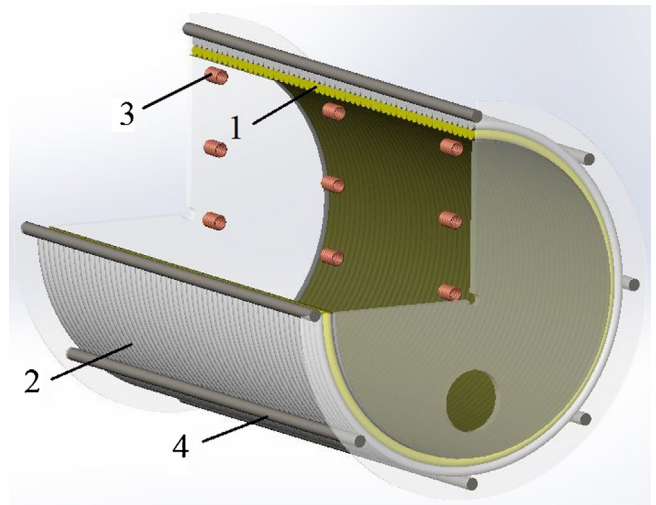


Fig. 2. The vacuum chamber of the CTC experiment (not to scale): 1 – main solenoid, 2 – auxiliary solenoid, 3 – B-probes, and 4 – reversed current electrodes.

formation with enhanced plasma energy. In all known experiments, the magnetic flux trapping does not exceed the level of 30–40% for the best experimental shots. The compact toroid challenge (CTC) experiments performed up to 50% more efficiently than the best previous experiment [27].

This paper presents a new approach in the CT formation. Experiments on the CTC over the past few years have been focused on characterizing the formation of plasma with the high level of a trapped magnetic field. A new concept of compact configuration formation by using poloidal and toroidal magnetic fields is presented. The interaction of these fields establishes compact torus configuration. The toroidal component of the magnetic field B_t (produced by an axially directed electron beam) is weak compare to the B_p field. As a result, the proposed device can be treated as a field-reversed configuration (FRC).

2. Description of the experiment

The CTC was developed to provide a pulse mode, high plasma energy alternative to conventional FRC generation techniques that are based on the fast theta-pinch technology. Initial testing parameters are planned for 30–40 kA coil currents, 10–25 μ s discharge times, over-all diameter of 50 cm, and 85 cm length. For vacuum generation a diffusion pump is used. Residual pressure is about 0.1–5 mTorr. Ionization vacuum gauge is used for pressure measurements. The final plasma density was measured to be 10^{15} cm³.

The general view of the system is presented in Fig. 1, where one can see the experimental setup for creating the FRC. The electro-physical scheme of the device consists of the main solenoid 1, the auxiliary solenoid 2, the exploding wire 3, the current monitor 4, the main switch 5, the high voltage electrodes 6, 7, and the capacitor banks C1, C2 and C3 (480 μ F, 40 kV). C1 feeds the main solenoid, C2 is the capacitor battery for the auxiliary solenoid, and C3 is the capacitor bank for the axial current I_{ax} excitation as well as the toroidal field B_t .

Formation chamber consists of (1) the main solenoid, (2) the auxiliary solenoid, (3) the B-probes, and (4) the reversed current electrodes (Fig. 2). The electric circuit is shown in Fig. 3. There are three main circuits: for the main solenoid, auxiliary solenoid and for axial current discharge.

The maximum charging voltage is 40 kV, which allows storing around 4 MJ power. However, current experiments have the voltage rarely above 25 kV. Experiments were conducted in a composite dielectric vacuum chamber. Usual level of energy stored in capacitors was about 50 kJ, characteristic configuration life-time was about 60 μ s. The photographs of the CTC experiments, made by a camera shooting at 1200 fps are presented in Fig. 4.

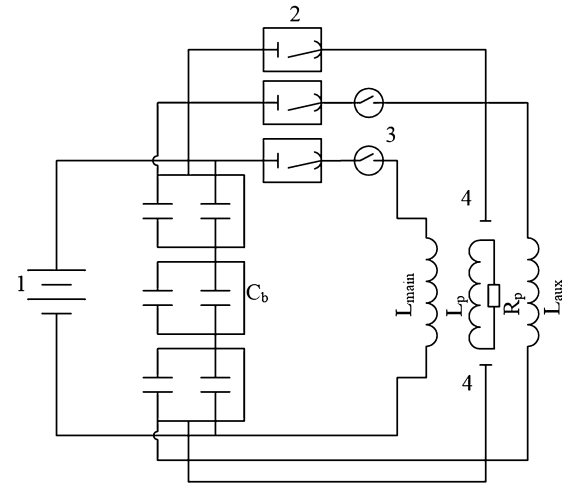


Fig. 3. The electrical circuit for CTC device discharge configuration: C_b is the capacitor bank capacitance, L_{main} and L_{aux} are the winding inductances, L_p and R_p are the plasma inductance and resistance, 1 is a charger, 2 is high voltage dischargers, 3 is current interrupters, 4 is axial current electrodes.

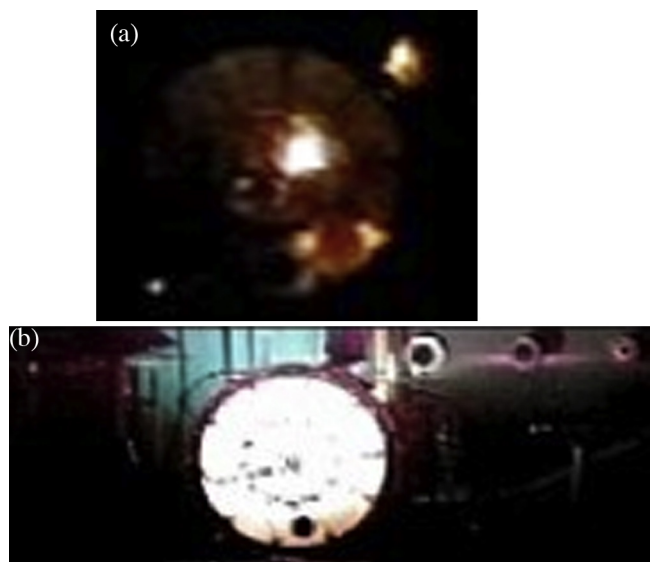


Fig. 4. Experimental shots.

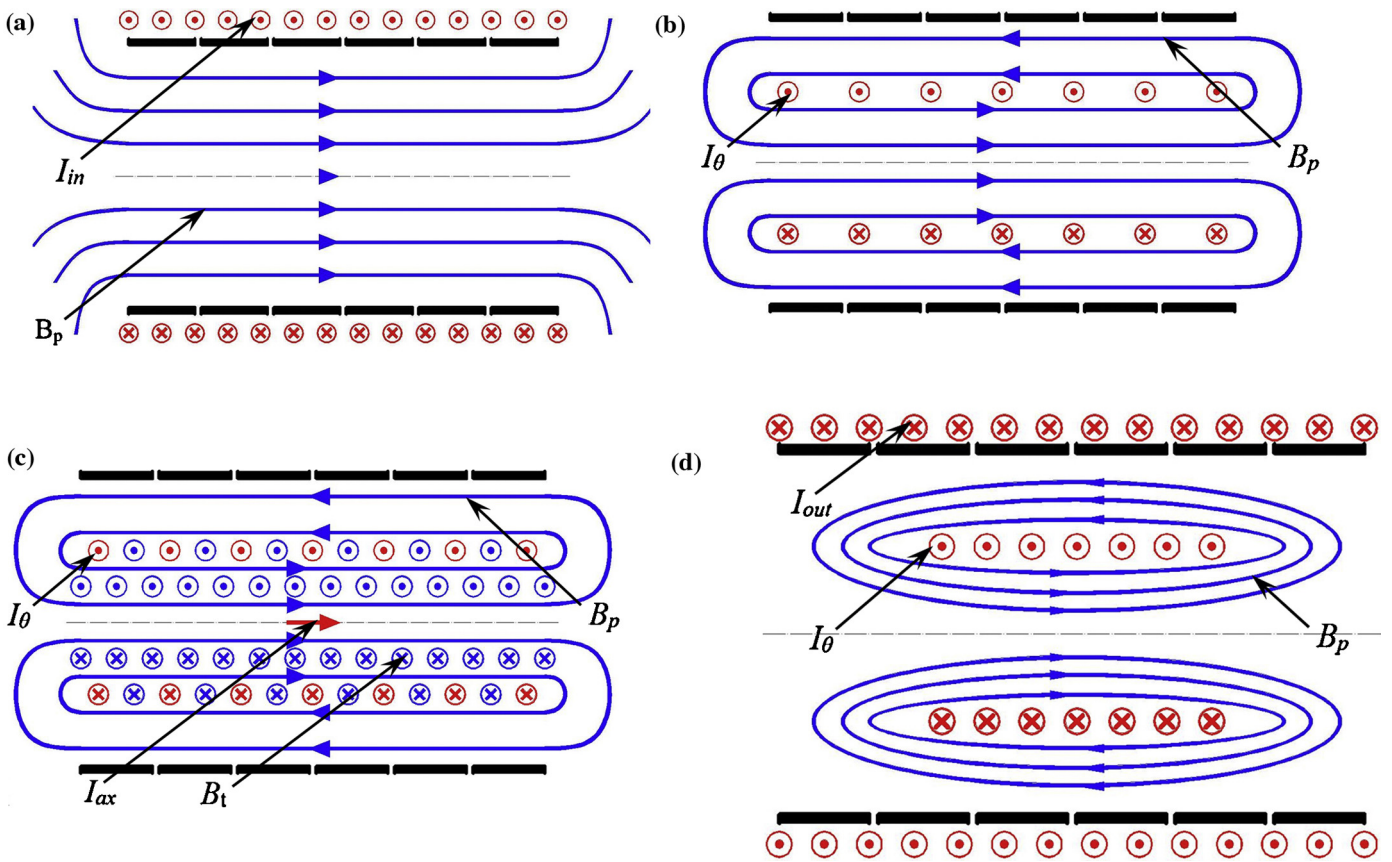


Fig. 5. Compact torus formation: I_{in} is the azimuthal current (the main coil), B_p is the poloidal magnetic field, I_θ is the azimuthal plasma current, I_{ax} is the axial current, B_t is the toroidal magnetic field, I_{out} is the auxiliary solenoid current.

3. Basic concept of the compact toroid formation and experimental results

Formation of a CT with a maximum input of energy and the capture of the magnetic field into plasma is an important scientific and technical challenge. The proposed method of formation is similar to the formation of FRC based on θ -pinch, but has some differences (Fig. 5):

Stage 1. The main capacitor bank C1 is discharged to the main solenoid 1, which covers the working volume A. It causes the azimuthal current I_{in} in solenoid. Poloidal magnetic field B_p appears simultaneously to this process. At the time, when the current reaches its maximum the whole energy is accumulated in the magnetic field and the current is terminated. This leads to a change of magnetic flux through the plasma, and eventually induces current in the plasma.

Stage 2. The azimuthal current I_θ arises in the plasma after the current I_{in} was terminated. This aims to support the decreasing magnetic field due to mutual induction. Since the external current decreases the plasma current I_θ runs in the same direction as the current in the main solenoid, according to Lenz's law. As in a usual transformer, the current can be kN times stronger than the current in the solenoid, where N is the number of turns in the solenoid, and k is a conditional coupling coefficient between the turns of the solenoid and the current-carrying loop in the plasma. The poloidal magnetic field B_p generates around the current I_θ .

Stage 3. The axial current capacitor C3 discharges at the time when the I_{in} current is terminated. This leads to the I_{ax} current flow through the center of the formation chamber and creates the toroidal component of the magnetic field B_t . The total magnetic field becomes helical (not shown). The electrons and ions begin

to move along the toroidal magnetic field lines and contribute to the azimuthal current I_θ . Azimuthal current I_θ creates a poloidal magnetic field B_p around itself. As a matter of fact, the resulting configuration is a compact elongated torus.

Stage 4. The axial current I_{ax} termination is followed by the auxiliary capacitor bank C2 discharge in order to create a current I_{out} . This causes plasma movement from the wall by Ampere's force between the current I_{out} and the azimuthal current I_θ . Main idea is to guarantee compression, confinement and heating the plasma.

Some experimental results were obtained on CT setup in FIAN. Our intentions were focused on measurements of a magnetic field and its evolution over time. Magnetic field probes, which are shown in Fig. 2, were used to record the data from the experiment. Due to the form of these sensors signals we can track the configuration evolution as well as a level of linked magnetic flux. Typical experimental sequence diagram is presented in Fig. 6. The first quarter-period sine curve is a poloidal magnetic field generation stage. After current is cut off there is abrupt signal decay caused by concentration relaxation after the current cut-off. The axial current pulse will go down to 0 almost immediately without having the second part of the period.

The CTC experiments were conducted without (Fig. 6) and with (Fig. 7) the compression. A compact torus-like configuration with a lifetime of $40 \mu s$ (Figs. 2 and 6) was created using the main solenoid and the longitudinal current. The waveforms of current and magnetic field with the windings current are shown in Fig. 6. Waveforms of magnetic field pulses in the center of chamber show the high compression (magnetic peak, following after current cut off). There is an abrupt increase in magnetic field (curve 6), indicating a strong compression in the longitudinal and transversal

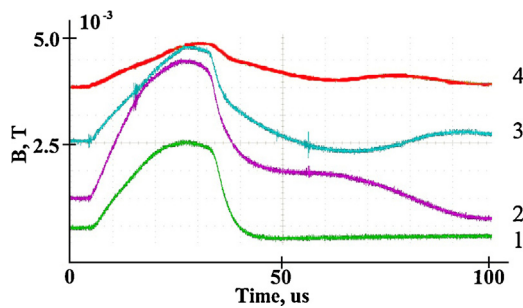


Fig. 6. Evolution of the magnetic field at the chamber wall (4), the magnetic field at the radius 12.5 cm (3), the magnetic field at the center of the chamber (2), and the current flowing through the solenoid storage (1).

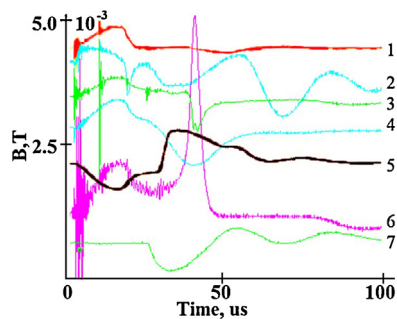


Fig. 7. Typical waveform with windings current, voltage on exploding wire: 1 – the main solenoid current, 2 – the circuit breaker voltage, 3 – the magnetic field at radius 12.5 cm, right, 4 – the magnetic field at radius 12.5 cm, left, 5 – the magnetic field at radius 12.5 cm at the center, 6 – the magnetic field at the center of the chamber, 7 – the auxiliary solenoid current.

directions, and hence its heating. The configuration lifetime is increased to 50–60 μ s.

We can clearly see from Fig. 7 that the current in the auxiliary solenoid (7) leads to the signal reversal in all the sensors except the central one (6), where we observe an increase in the magnetic field. This peak indicates high compression of the formed current-carrying loop in both radial and longitudinal directions and formation of compact toroid.

The magnetic field in the plasma (the magnetic flux that is embedded in the plasma) may not exceed 40% of an initial magnetic field. The compact toroid challenge (CTC) experiments with about 50 kJ of stored energy in the capacitors provided more than 70% level of residual magnetic flux.

4. Conclusions and future scope

We present some results on obtaining plasma with a high level of linked magnetic flux in the compact toroid magnetic topology, allowing for compression, confinement and heating plasma. The paper reports on the results of experimental research on compact toroid formation. We discussed compact toroid challenge (CTC) experiment at FIAN, where a compact toroid is produced and confined in a theta-pinch-coil with pulse mode of operation.

The main parameter of measurements is the magnetic field and its change in time and over the volume of the chamber. Nine magnetic field probes were used to record the data from the experiment. We concentrated our efforts on the magnetic flux trapping and possibility of using such a method for creating a compact toroid plasma.

A new measurement system is under construction and improved experimental technique will be used in a future set of experiments.

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