



Design, Fabrication, and Experimental Validation of Magnetic Field Coils for a Compact Table-Top Tokamak System

Jayrajsinh B. Solanki

Abstract—Compact tokamak systems provide a cost-effective platform for investigating magnetic confinement principles, plasma initiation mechanisms, and educational research in fusion technology. The performance of such systems is largely governed by the design and implementation of magnetic field coils responsible for plasma current induction and confinement. This paper presents the analytical design, fabrication, electromagnetic analysis, and experimental validation of a magnetic field coil system developed for a compact table-top tokamak. The proposed system comprises a central solenoid coil for plasma current induction and a toroidal field coil assembly for magnetic confinement.

The design methodology is based on tokamak physics requirements and electromagnetic design principles, including plasma current, toroidal magnetic field strength, safety factor, and geometric constraints. Coil parameters such as the number of turns, conductor dimensions, inductance, resistance, stored magnetic energy, and current-carrying capability were determined through analytical calculations. A capacitor-discharge pulsed power supply incorporating a Cockcroft-Walton voltage multiplier and SCR-based switching circuit was developed to generate the high-current pulses required for coil excitation.

The fabricated coils were characterized experimentally and compared with analytical and numerical predictions. The central solenoid coil generated a peak magnetic field of approximately 1.4 T, while the toroidal field coil assembly produced the magnetic field distribution required for compact tokamak operation. The voltage multiplier successfully generated an output voltage of approximately 1.3 kV, and the central solenoid coil achieved a peak discharge current of 88 A during pulsed operation. Finite-element electromagnetic analysis further validated the magnetic field distribution and coil performance.

The close agreement among analytical calculations, electromagnetic simulations, and experimental measurements confirms the effectiveness of the proposed design methodology. The developed magnetic field system provides a practical and economical platform for laboratory-scale tokamak experiments and educational research in magnetic confinement fusion.

Index Terms—Compact tokamak, magnetic confinement fusion, central solenoid coil, toroidal field coil, pulsed power supply, Cockcroft-Walton voltage multiplier, electromagnetic analysis, experimental validation.

I. INTRODUCTION

Nuclear fusion is widely recognized as one of the most promising long-term solutions for sustainable energy generation due to its high energy density, abundant fuel resources,

and environmentally benign operation. Among the various fusion concepts investigated over the past several decades, magnetic confinement fusion has emerged as the most mature approach, with the tokamak becoming the most successful configuration for achieving high-temperature plasma confinement [1], [2]. In a tokamak, plasma is confined within a toroidal vacuum chamber by the combined action of toroidal and poloidal magnetic fields. The toroidal magnetic field is generated by external toroidal field coils, whereas the poloidal magnetic field is primarily produced by plasma current induced through a central solenoid system. The superposition of these magnetic fields forms helical field lines that improve particle confinement and plasma stability [3], [4].

Significant progress in tokamak research has been achieved through large-scale fusion facilities such as JET, JT-60, DIII-D, EAST, KSTAR, and ITER. These devices have demonstrated substantial advances in plasma confinement, heating, and control technologies, bringing fusion energy closer to practical realization [5], [6]. However, the construction and operation of large fusion devices require extensive infrastructure, sophisticated technologies, and considerable financial resources. Consequently, their accessibility is generally limited to national laboratories and large international collaborations.

To address these limitations, several compact and educational tokamak systems have been developed as low-cost platforms for studying plasma initiation, magnetic confinement principles, electromagnetic diagnostics, and control techniques [7], [8]. Although such systems operate at significantly lower plasma currents and magnetic field strengths than large fusion devices, they provide valuable opportunities for understanding tokamak engineering and plasma physics concepts. Compact tokamaks also offer an effective experimental environment for validating magnetic field generation techniques and pulsed power systems before implementation in larger fusion devices.

Figure 1 illustrates the basic configuration of a compact table-top tokamak consisting of a central solenoid coil, toroidal field coils, vacuum vessel, and plasma region. The central solenoid acts as the primary winding of a transformer and induces plasma current within the vacuum vessel, while the toroidal field coils generate the magnetic field required for plasma confinement. The overall performance of the tokamak strongly depends on the design and implementation of these magnetic field systems.

The magnetic field coil system represents one of the most critical subsystems of any tokamak device. Parameters such as ampere-turns, inductance, resistance, stored magnetic energy,

J. B. Solanki is with the Department of Electrical Engineering, B. & B. Institute of Technology, Vallabh Vidyanagar, Anand-388120, Gujarat, India (e-mail: jayraj_ee@yahoo.co.in).

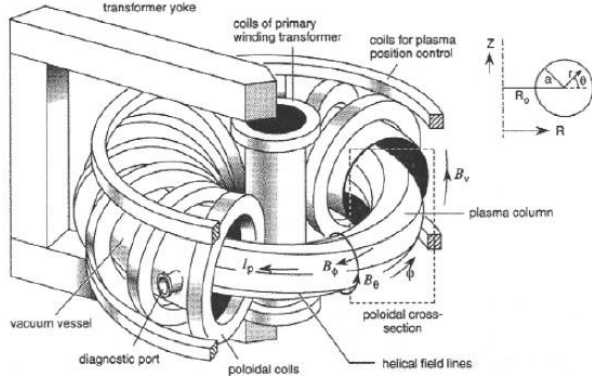


Fig. 1: Basic configuration of a compact table-top tokamak showing the central solenoid coil, toroidal field coils, vacuum vessel, and plasma column.

conductor dimensions, and magnetic field strength directly influence plasma initiation and confinement performance [9], [10]. Several studies have investigated plasma equilibrium, electromagnetic modelling, and tokamak control using analytical, numerical, and finite-element approaches [11]–[13]. Nevertheless, comparatively fewer studies have reported the complete engineering realization of magnetic field coils for compact educational tokamaks, including analytical design, fabrication, pulsed power implementation, electromagnetic verification, and experimental validation.

This paper presents the design, fabrication, electromagnetic analysis, and experimental validation of a magnetic field coil system developed for a compact table-top tokamak. The proposed system consists of a central solenoid coil, a toroidal field coil assembly, and a capacitor-discharge pulsed power supply incorporating a Cockcroft-Walton voltage multiplier. Analytical calculations, finite-element electromagnetic simulations, and experimental investigations are performed to evaluate the electrical and magnetic performance of the developed system.

The major contributions of this work are summarized as follows:

- 1) Development of a low-cost magnetic field coil system for a compact table-top tokamak.
- 2) Analytical design methodology for central solenoid and toroidal field coils based on tokamak physics requirements.
- 3) Design and implementation of a capacitor-discharge pulsed power supply employing a Cockcroft-Walton voltage multiplier and SCR-based switching circuit.
- 4) Experimental validation of coil inductance, resistance, discharge current, and magnetic field generation capability.
- 5) Electromagnetic verification of magnetic field distribution using finite-element analysis and comparison with experimental measurements.

““latex

II. DESIGN REQUIREMENTS AND TOKAMAK PARAMETERS

The design of a compact tokamak requires the selection of plasma operating conditions and machine dimensions capable

of producing the magnetic fields necessary for plasma initiation and confinement. Unlike large fusion reactors, whose design is primarily driven by fusion power production requirements, compact tokamaks are generally intended for plasma physics experiments, educational studies, electromagnetic investigations, and diagnostic development. Consequently, the design process focuses on achieving stable plasma formation while maintaining manageable dimensions, moderate power requirements, and simplified engineering implementation [5], [14], [15].

The design methodology adopted in this work follows the conventional tokamak design sequence consisting of plasma parameter selection, machine geometry determination, magnetic field requirement estimation, magnetic coil design, pulsed power supply development, fabrication, and experimental validation. The selected parameters were derived from published design practices for compact tokamaks and educational plasma confinement devices reported in the literature [16]–[19].

A. Plasma Design Parameters

The plasma parameters determine the machine dimensions, magnetic field requirements, plasma current, and overall electromagnetic characteristics of the tokamak. For the proposed compact table-top tokamak, the design parameters were selected to provide stable plasma operation while maintaining practical construction constraints.

The plasma density was selected as approximately $2 \times 10^{19} \text{ m}^{-3}$, which lies within the operational range reported for compact tokamak devices [20], [21]. The electron temperature was selected as 120 eV, while the energy confinement time was chosen as 0.325 ms to permit plasma initiation studies using a capacitor-discharge pulsed power system.

The edge safety factor was fixed at $q = 3$, which represents a commonly accepted operating region for stable tokamak operation [12], [22].

TABLE I: Design Parameters of the Proposed Compact Tokamak

Parameter	Symbol	Value
Major Radius	R	23 cm
Minor Radius	a	7.2 cm
Toroidal Magnetic Field	B_t	0.54 T
Poloidal Magnetic Field	B_p	0.054 T
Safety Factor	q	3
Plasma Current	I_p	20.638 kA
Plasma Density	n	$2 \times 10^{19} \text{ m}^{-3}$
Electron Temperature	T_e	120 eV
Confinement Time	τ	0.325 ms
Aspect Ratio	A	3.19

Figure 2 illustrates the principal dimensions of the proposed compact tokamak.

B. Tokamak Geometry Selection

The geometry of a tokamak is primarily characterized by its major radius (R) and minor radius (a). The aspect ratio is defined as

$$A = \frac{R}{a} \quad (1)$$

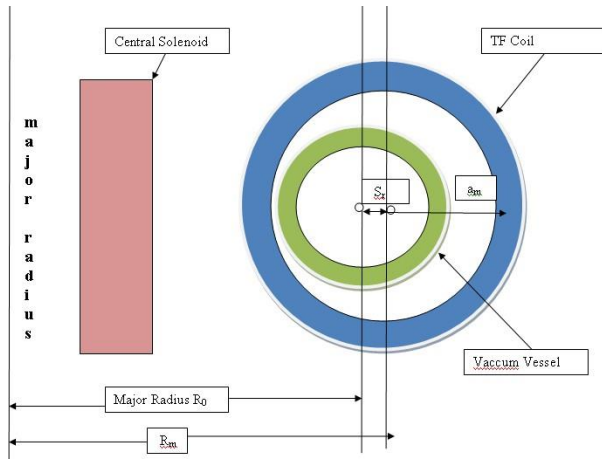


Fig. 2: Principal geometrical dimensions of the compact table-top tokamak.

where A represents the aspect ratio of the tokamak. For the selected dimensions,

$$A = \frac{0.23}{0.072} = 3.19 \quad (2)$$

which lies within the typical range adopted for compact tokamak systems [17], [18].

C. Plasma Current Requirement

The plasma current generates the poloidal magnetic field required for equilibrium and confinement. According to tokamak equilibrium theory, the plasma current can be estimated as

$$I_p = \frac{5a^2 B_t}{Rq} \quad (3)$$

where I_p is the plasma current, a is the plasma minor radius, R is the major radius, B_t is the toroidal magnetic field, and q is the safety factor.

Substituting the selected design parameters results in a plasma current requirement of approximately 20.638 kA.

The corresponding poloidal magnetic field at the plasma boundary is given by

$$B_p = \frac{\mu_0 I_p}{2\pi a} \quad (4)$$

where μ_0 is the permeability of free space.

D. Density and Confinement Considerations

The Greenwald density limit provides an important constraint for stable tokamak operation and can be expressed as

$$n_G = \frac{I_p}{\pi a^2} \quad (5)$$

where n_G is the density limit and I_p is expressed in mega-amperes.

The selected plasma density remains below the Greenwald limit, ensuring stable operation under the intended experimental conditions.

In addition, plasma confinement must satisfy the Lawson criterion,

$$n\tau \geq 10^{18} \quad (6)$$

which relates plasma density and confinement time to energy confinement requirements [15], [19].

E. Toroidal Magnetic Field Requirement

The toroidal magnetic field is the primary confinement field responsible for restricting the radial motion of charged particles. The field generated by the toroidal field coil assembly is approximated by

$$B_t = \frac{\mu_0 NI}{2\pi R} \quad (7)$$

where N is the number of turns, I is the coil current, and R is the major radius.

For the selected design parameters, the required toroidal magnetic field was fixed at 0.54 T. This corresponds to an ampere-turn requirement of approximately

$$NI = 6.21 \times 10^5 \text{ A-turns} \quad (8)$$

which forms the basis for the toroidal field coil design presented in the next section.

F. Central Solenoid Magnetic Field Requirement

The central solenoid functions as the primary winding of a transformer and induces plasma current through electromagnetic induction. The magnetic field generated by a solenoid is given by

$$B_{cs} = \mu_0 nI \quad (9)$$

where n is the number of turns per unit length and I is the excitation current.

To achieve reliable plasma breakdown and current induction, the central solenoid was designed to generate a peak magnetic field of approximately 1.4 T during pulsed operation.

G. Pulsed Power Requirement

A capacitor-discharge pulsed power supply was selected because of its simplicity, reliability, and suitability for short-duration plasma experiments. The energy stored in the capacitor bank is given by

$$E = \frac{1}{2} CV^2 \quad (10)$$

where E is the stored energy, C is the capacitance, and V is the charging voltage.

A charging voltage of approximately 1000 V was selected to provide the current levels required by both the central solenoid and toroidal field coils. The plasma parameters, machine geometry, and magnetic field requirements established in this section form the basis for the magnetic field coil design and fabrication presented in the following section.

““latex

III. DESIGN AND FABRICATION OF MAGNETIC FIELD COILS

The magnetic field system of the proposed compact tokamak consists of a toroidal field (TF) coil assembly and a central solenoid (CS) coil. The TF coils generate the primary toroidal magnetic field required for plasma confinement, whereas the CS coil acts as the primary winding of a transformer and induces plasma current within the vacuum vessel. The design of both coil systems was carried out based on the plasma parameters and machine dimensions established in Section II.

A. Toroidal Field Coil Design

The toroidal field coil assembly is responsible for producing the magnetic field required to confine charged particles within the plasma column. The design objective was to generate a toroidal magnetic field of approximately 0.54 T at the plasma center while maintaining compact dimensions and acceptable current levels.

For a toroidal magnetic field coil system, the magnetic field at the plasma center can be approximated by

$$B_t = \frac{2 \times 10^{-5} NI}{R} \quad (11)$$

where B_t is the toroidal magnetic field (T), N is the total number of turns, I is the coil current (A), and R is the major radius (cm).

The required ampere-turn product can therefore be expressed as

$$NI = \frac{B_t R}{2 \times 10^{-5}} \quad (12)$$

Substituting the design values $B_t = 0.54$ T and $R = 23$ cm yields

$$NI \approx 6.21 \times 10^5 \text{ A-turns} \quad (13)$$

To satisfy this requirement, a toroidal field coil assembly consisting of ten identical coils was selected. The coils were positioned symmetrically around the vacuum vessel to produce a nearly uniform toroidal magnetic field distribution.

The coil resistance was calculated using

$$R = \rho \frac{l}{A} \quad (14)$$

where ρ is the resistivity of copper, l is the conductor length, and A is the conductor cross-sectional area.

The magnetic energy stored in the toroidal field coil system is given by

$$E = \frac{1}{2} LI^2 \quad (15)$$

where L is the coil inductance and I is the coil current.

Figure 3 illustrates the fabricated toroidal field coil assembly.

The symmetrical arrangement of the ten TF coils minimizes magnetic field ripple and improves field uniformity within the plasma confinement region.

TABLE II: Design Parameters of the Toroidal Field Coil Assembly

Parameter	Value
Number of TF Coils	10
Turns per Coil	43
Total Turns	430
Major Radius	230 mm
Inner Radius	160 mm
Outer Radius	186 mm
Inductance	5.27 mH
Resistance	1.7 Ω
Design Magnetic Field	0.54 T



Fig. 3: Fabricated toroidal field coil assembly.

B. Central Solenoid Coil Design

The central solenoid coil acts as the primary winding of a transformer and is responsible for inducing plasma current within the vacuum vessel. The magnetic field generated by the solenoid is given by

$$B_{CS} = \mu_0 n I \quad (16)$$

where n is the number of turns per unit length and I is the excitation current.

The inductance of the solenoid coil was calculated using Wheeler's equation,

$$L = \frac{N^2 (0.2a^2)}{3a + 9l + 10(b - a)} \quad (17)$$

where

- N Number of turns
- a Outer radius
- b Inner radius
- l Coil length

The dimensions of the central solenoid were selected to generate a peak magnetic field of approximately 1.4 T while satisfying the available space constraints of the compact tokamak.

Figure 4 shows the fabricated central solenoid coil.

The measured inductance differed from the analytical value by less than 10%, indicating good agreement between theoretical design and fabricated hardware.

TABLE III: Design Parameters of the Central Solenoid Coil

Parameter	Value
Inner Radius	41 mm
Outer Radius	61 mm
Length	330 mm
Number of Turns	540
Calculated Inductance	8.23 mH
Measured Inductance	7.55 mH
Resistance	1.1 Ω
Peak Magnetic Field	1.4 T

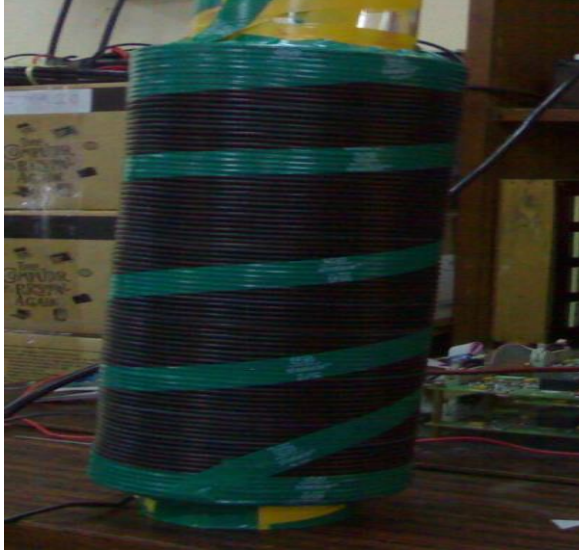


Fig. 4: Fabricated central solenoid coil.

C. Pulsed Power Considerations

Both magnetic field coil systems were designed for operation using a capacitor-discharge pulsed power supply. The energy stored in the capacitor bank is

$$E = \frac{1}{2} CV^2 \quad (18)$$

where C is the capacitance and V is the charging voltage. The peak discharge current can be estimated using

$$I_{peak} = V \sqrt{\frac{C}{L}} \quad (19)$$

while the characteristic impedance of the discharge circuit is

$$Z = \sqrt{\frac{L}{C}} \quad (20)$$

The pulsed power system was designed to operate at charging voltages approaching 1 kV and to generate the high-current pulses required for magnetic field production.

D. Fabrication of Magnetic Field Coils

The TF and CS coils were fabricated using insulated copper conductors wound on non-magnetic support structures. Mechanical fixtures were incorporated to withstand the electromagnetic forces generated during pulsed operation. After

winding, the coils were tested for continuity, insulation integrity, resistance, and inductance before integration with the pulsed power supply.

Figure 3 and 4 presents the fabrication stages of the developed magnetic field coils. The fabricated magnetic field coil system constitutes the core subsystem of the compact tokamak and provides the electromagnetic environment required for plasma initiation and confinement studies.

““latex

IV. PULSED POWER SUPPLY DESIGN AND IMPLEMENTATION

The magnetic field coils of the proposed compact tokamak require short-duration high-current pulses for plasma initiation and magnetic confinement studies. Since continuous operation is not required for laboratory-scale investigations, a capacitor-discharge pulsed power supply was selected. This approach provides a simple, economical, and reliable means of generating high-current pulses while minimizing system complexity and overall system cost.

The developed pulsed power supply consists of four major subsystems:

- High-voltage charging unit
- Cockcroft-Walton voltage multiplier
- Capacitor bank energy storage system
- SCR-based pulse discharge circuit

Figure 5 illustrates the overall architecture of the developed pulsed power system.

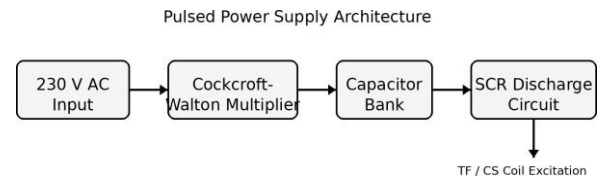


Fig. 5: Block diagram of the pulsed power supply system.

A. Power Supply Requirements

The toroidal field coil assembly and central solenoid coil require high-current pulses to generate the magnetic fields necessary for tokamak operation. Based on the magnetic field requirements established in Section III, the power supply was designed to satisfy the following specifications:

- Output voltage exceeding 1 kV
- High-current pulse generation
- Fast discharge capability
- Electrical isolation from the mains supply
- Repeatable pulsed operation
- Compact and economical implementation

The energy stored in the capacitor bank is given by

$$E = \frac{1}{2} CV^2 \quad (21)$$

where E is the stored energy (J), C is the capacitance (F), and V is the charging voltage (V).

The stored energy determines the maximum electromagnetic energy available for magnetic field generation during coil excitation.

B. Cockcroft-Walton Voltage Multiplier

A four-stage Cockcroft-Walton voltage multiplier was employed to generate the high-voltage DC output required for charging the capacitor bank. The circuit consists of four high-voltage diodes and four capacitors connected in a cascade arrangement. This configuration converts a low-voltage AC input into a high-voltage DC output without requiring a bulky high-voltage transformer.

Figure 6 shows the voltage multiplier circuit developed for the compact tokamak system.

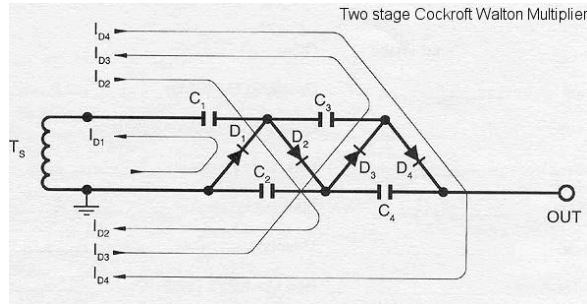


Fig. 6: Four-stage Cockcroft-Walton voltage multiplier circuit.

The output voltage of an ideal n -stage Cockcroft-Walton multiplier is approximated by

$$V_o = 2nV_m \quad (22)$$

where V_o is the output voltage, n is the number of stages, and V_m is the peak AC input voltage.

The developed multiplier successfully generated an output voltage of approximately 1.3 kV, which was used to charge the capacitor bank for pulsed operation.

C. Capacitor Bank Design

The capacitor bank serves as the primary energy storage element of the pulsed power system. During operation, electrical energy is accumulated within the capacitor bank and subsequently released through the magnetic field coils.

The characteristic impedance of the discharge circuit is given by

$$Z = \sqrt{\frac{L}{C}} \quad (23)$$

where L is the circuit inductance and C is the capacitance. The natural angular frequency of the discharge circuit is

$$\omega = \frac{1}{\sqrt{LC}} \quad (24)$$

The oscillation frequency is therefore

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (25)$$

These parameters determine the pulse width, current rise time, and overall discharge characteristics of the system.

D. SCR-Based Pulse Discharge Circuit

A silicon controlled rectifier (SCR) was employed as the primary switching device for capacitor discharge. After the capacitor bank reaches the desired charging voltage, a trigger pulse is applied to the SCR gate, initiating rapid energy transfer to the selected magnetic field coil.

Figure 7 illustrates the SCR-based pulse discharge circuit.

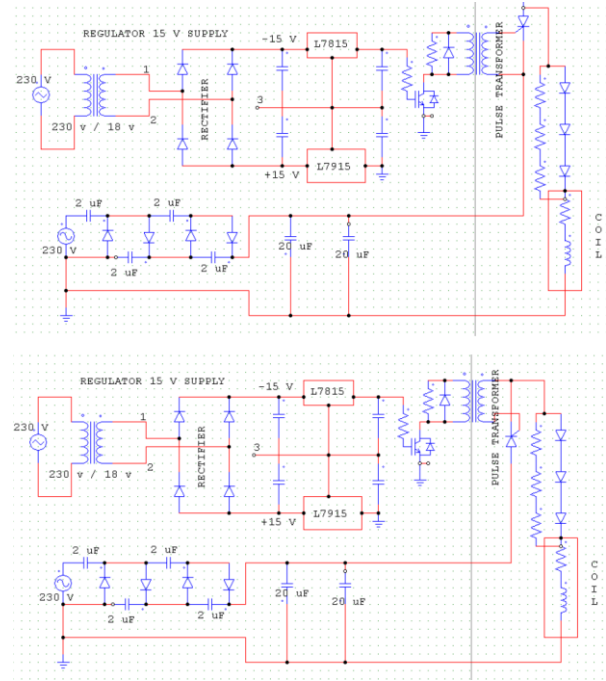


Fig. 7: SCR-based capacitor discharge circuit.

The peak discharge current can be estimated using

$$I_{peak} = V \sqrt{\frac{C}{L}} \quad (26)$$

where I_{peak} is the peak current, V is the charging voltage, C is the capacitance, and L is the circuit inductance.

The SCR was selected to withstand the maximum charging voltage and peak current encountered during pulsed operation.

E. Experimental Power Supply Setup

The fabricated pulsed power supply consists of the Cockcroft-Walton voltage multiplier, capacitor bank, charging circuit, triggering circuit, SCR switching unit, and protection circuitry. Appropriate insulation and grounding measures were implemented because of the presence of high-voltage components.

Figure 8 shows the fabricated pulsed power supply used during experimental investigations.

F. Power Supply Specifications

Table IV summarizes the principal specifications of the developed pulsed power supply.

The developed pulsed power supply successfully generated repeatable high-current pulses required for energizing both



Fig. 8: Experimental pulsed power supply system.

TABLE IV: Power Supply Specifications

Parameter	Value
Input Voltage	230 V AC
Voltage Multiplier Stages	4
Capacitors	$4 \times 2 \mu\text{F}$
Output Voltage	1.3 kV DC
Switching Device	SCR
Energy Storage Element	Capacitor Bank
Operating Mode	Capacitor Discharge
Application	TF and CS Coil Excitation

the toroidal field and central solenoid coils. Experimental measurements confirmed stable charging characteristics, reliable SCR switching operation, and effective pulse generation suitable for compact tokamak applications.

V. EXPERIMENTAL SETUP AND MEASUREMENT PROCEDURE

The fabricated magnetic field coils and pulsed power supply were integrated to establish a compact experimental tokamak platform. Experimental investigations were conducted to validate the analytical design calculations and evaluate the electrical and magnetic performance of the developed system. The experimental setup consisted of the central solenoid coil, toroidal field coil assembly, Cockcroft-Walton voltage multiplier, capacitor bank, SCR-based pulse discharge circuit, and measurement instrumentation.

A. Experimental Setup

Figure 9 illustrates the complete experimental arrangement employed for testing the magnetic field coil system.

The capacitor bank was charged using the Cockcroft-Walton voltage multiplier and subsequently discharged through the selected magnetic field coil using an SCR-based switching circuit. Voltage and current waveforms were monitored using a digital storage oscilloscope, while inductance and resistance measurements were obtained using standard laboratory instruments.

The principal measurement equipment used during the experimental investigations is summarized in Table V.



Fig. 9: Overall experimental setup of the compact tokamak magnetic field system.

TABLE V: Experimental Measurement Equipment

Equipment	Purpose
Digital Oscilloscope	Voltage and current measurement
Current Probe	Pulse current measurement
LCR Meter	Coil inductance measurement
Digital Multimeter	Resistance measurement
Gauss Meter	Magnetic field measurement

B. Central Solenoid Coil Testing

The central solenoid coil was tested independently to verify its inductance, resistance, discharge current capability, and magnetic field generation performance. During testing, the capacitor bank was charged to the desired voltage level and discharged through the coil. The resulting current and voltage waveforms were recorded using a digital storage oscilloscope.

Figure 9 shows the experimental arrangement employed for central solenoid coil characterization.

C. Toroidal Field Coil Testing

The toroidal field coil assembly was evaluated using a similar procedure. The objective was to verify the ability of the coil system to generate the required toroidal magnetic field and to assess the repeatability of pulsed operation.

The current waveform, coil inductance, coil resistance, and magnetic field distribution were measured and compared with analytical calculations.

Figure 10 presents the experimental arrangement used for toroidal field coil testing.

““latex

VI. EXPERIMENTAL AND ELECTROMAGNETIC VALIDATION

The fabricated magnetic field coil system and pulsed power supply were experimentally evaluated to verify the analytical design calculations and electromagnetic performance. Experimental measurements were performed on the voltage multiplier, central solenoid coil, and toroidal field coil assembly. In addition, finite-element electromagnetic simulations were



Fig. 10: Experimental setup for toroidal field coil testing.

conducted using the Integrated Engineering Software (IES) package to validate magnetic field distribution and flux density predictions.

A. Validation of the Pulsed Power Supply

A four-stage Cockcroft-Walton voltage multiplier was developed to generate the high-voltage DC output required for capacitor charging. The multiplier consisted of four high-voltage diodes and four 2 μ F capacitors connected in a cascade configuration.

Figure 6 shows the fabricated voltage multiplier circuit, while Fig. 11 presents the measured output voltage waveform.

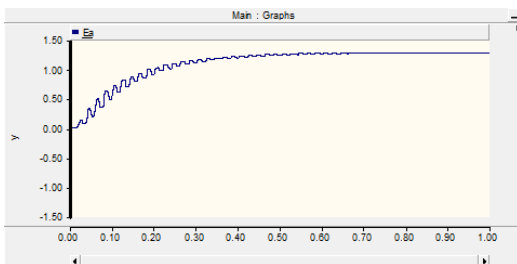


Fig. 11: Measured output voltage waveform of the voltage multiplier.

Experimental measurements confirmed that the voltage multiplier generated an output voltage of approximately 1.3 kV. The capacitor bank charging process remained stable and repeatable throughout the experimental investigations.

B. Central Solenoid Coil Validation

The fabricated central solenoid coil was experimentally evaluated using the capacitor-discharge pulsed power supply. The measured inductance was 7.55 mH compared with the calculated value of 8.23 mH, corresponding to a deviation of approximately 8.3%.

The capacitor bank was charged to approximately 1000 V and discharged through the coil. Experimental measurements indicated a peak discharge current of approximately 88 A, while the theoretical and PSCAD simulation results were 72 A and 68.5 A, respectively.

Figure 12 shows the experimental setup and measured current waveform.

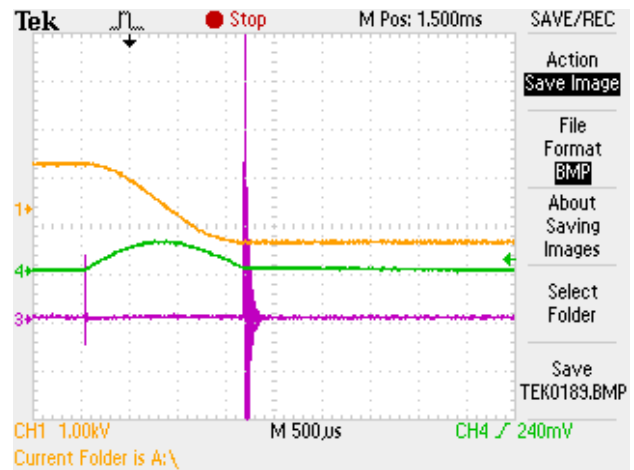


Fig. 12: Experimental current waveform of the central solenoid coil during capacitor-discharge pulsed operation.

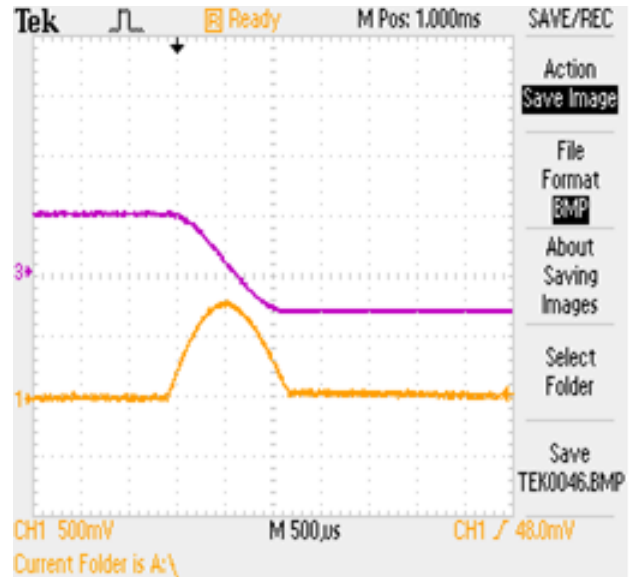


Fig. 13: Experimental current waveform of the toroidal field coil assembly during capacitor-discharge pulsed operation (Ch1: Coil current = 82.4 A, Ch2: Capacitor voltage = 1000 V).

The generated magnetic field reached approximately 1.4 T, confirming the capability of the coil to provide the magnetic flux required for plasma current induction.

C. Toroidal Field Coil Validation

The toroidal field coil assembly consisted of ten identical coils arranged symmetrically around the vacuum vessel. The assembly was energized using the capacitor-discharge system and tested under pulsed operating conditions.

Experimental measurements indicated a peak discharge current of approximately 82.4 A and stable operation throughout the discharge interval. The generated magnetic field distribution confirmed the ability of the coil system to establish the magnetic confinement field required for compact tokamak operation.

D. Finite-Element Electromagnetic Analysis

Finite-element electromagnetic simulations were performed using the IES package to verify the analytical design methodology and investigate magnetic field distribution within the magnetic field coil system.

Figure 14 and Fig. 15 show the finite-element mesh model and magnetic flux density distribution of the central solenoid coil.

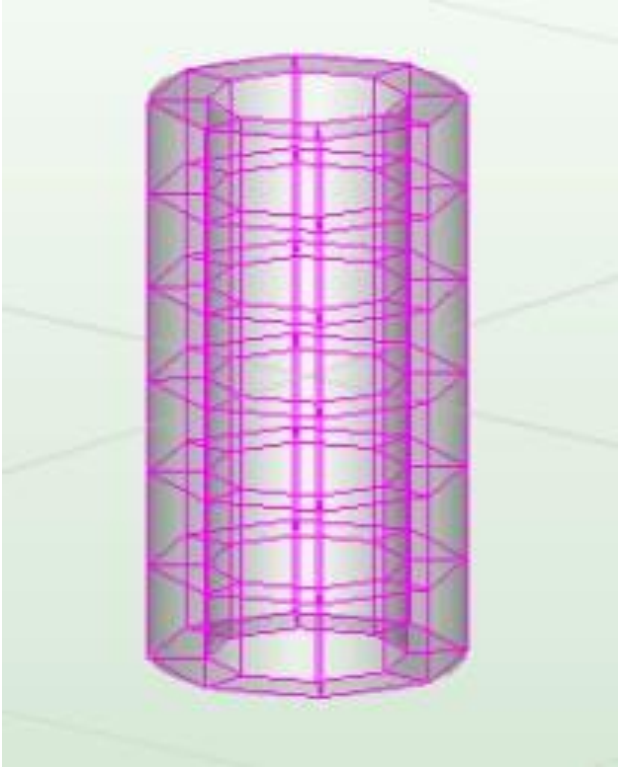


Fig. 14: Finite-element mesh model of the central solenoid coil.

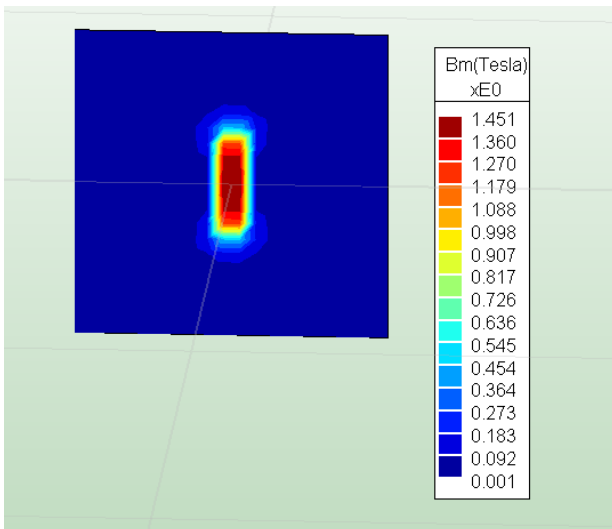


Fig. 15: Magnetic flux density distribution of the central solenoid coil.

The maximum simulated magnetic flux density was approximately 1.56 T, which is in close agreement with the analytical design value of 1.40 T.

Similarly, the toroidal field coil assembly was analyzed using finite-element modelling.

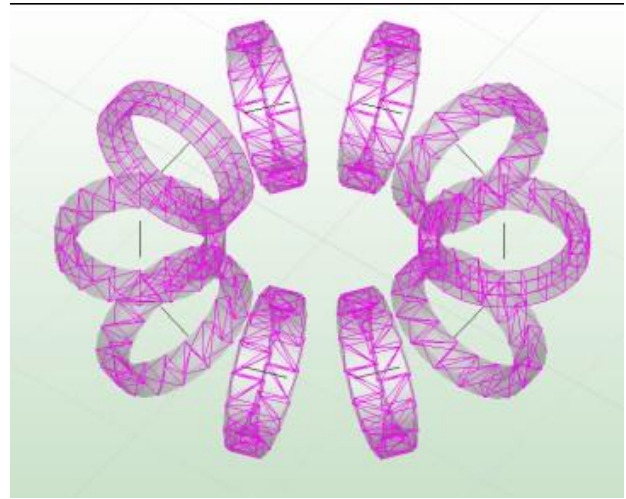


Fig. 16: Finite-element model of the toroidal field coil assembly.

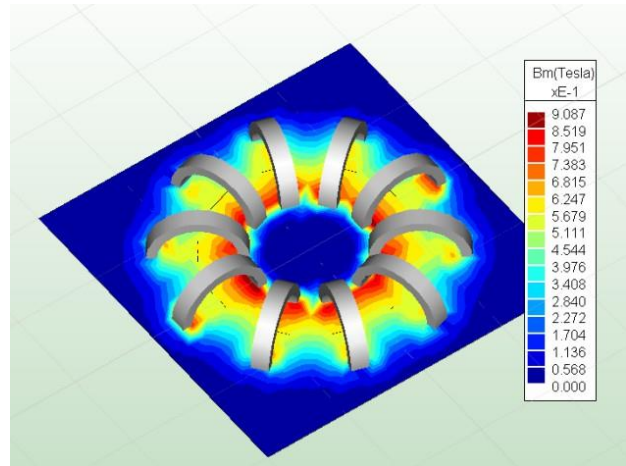


Fig. 17: Magnetic flux density distribution of the toroidal field coil assembly.

The maximum simulated toroidal magnetic field was approximately 0.56 T, compared with the design value of 0.54 T.

E. Comparative Validation and Discussion

The percentage deviation between analytical and simulation results was calculated using

$$\text{Error(\%)} = \frac{|X_{sim} - X_{theory}|}{X_{theory}} \times 100 \quad (27)$$

Table VI summarizes the comparison among analytical calculations, numerical simulations, and experimental measurements.

TABLE VI: Comparison of Analytical, Simulation, and Experimental Results

Parameter	Theory	Simulation	Experiment
CS Magnetic Field (T)	1.40	1.56	1.37
TF Magnetic Field (T)	0.54	0.56	0.52
CS Coil Current (A)	72.0	68.5	88.0
TF Coil Current (A)	78.0	78.3	82.4
CS Coil Inductance (mH)	8.23	—	7.55

The results demonstrate good agreement among analytical calculations, finite-element simulations, and experimental measurements. Minor deviations are attributed to manufacturing tolerances, parasitic circuit parameters, conductor resistance variations, and measurement uncertainties. Overall, the developed magnetic field system successfully achieved the design objectives and demonstrated reliable operation for compact tokamak applications. ““latex

VII. CONCLUSION

This paper presented the design, fabrication, and validation of a magnetic field system for a compact table-top tokamak. The developed system comprised a central solenoid coil, a toroidal field coil assembly, and a capacitor-discharge pulsed power supply employing a four-stage Cockcroft-Walton voltage multiplier and SCR-based switching circuit. The design methodology was established using tokamak physics requirements and electromagnetic design principles to achieve the magnetic field levels necessary for plasma initiation and confinement studies.

The central solenoid coil was designed and fabricated to generate the magnetic flux required for plasma current induction, while the toroidal field coil assembly provided the magnetic confinement field within the plasma region. Experimental investigations demonstrated successful operation of both magnetic field systems. The central solenoid coil generated a peak magnetic field of approximately 1.4 T and achieved a peak discharge current of 88 A. Similarly, the toroidal field coil assembly produced a magnetic field close to the design target of 0.54 T and achieved a peak discharge current of 82.4 A under pulsed operating conditions.

The developed pulsed power supply successfully generated a charging voltage of approximately 1.3 kV and provided stable, repeatable high-current pulses for coil excitation. Finite-element electromagnetic analysis further verified the proposed design methodology, with simulated magnetic field values of approximately 1.56 T for the central solenoid coil and 0.56 T for the toroidal field coil assembly. The close agreement among analytical calculations, numerical simulations, and experimental measurements confirms the validity of the proposed design approach.

The results demonstrate that a low-cost magnetic field system based on copper coils and capacitor-discharge pulsed power technology can provide an effective platform for laboratory-scale tokamak experiments and educational plasma research. The proposed design methodology may serve as a useful reference for the development of compact magnetic confinement devices, plasma engineering experiments, and future small-scale fusion research facilities.

Future work will focus on vacuum vessel integration, plasma breakdown experiments, implementation of diagnostic systems, and investigation of plasma confinement characteristics under different operating conditions.

REFERENCES

- [1] J. Wesson, *Tokamaks*, 4th ed. Oxford University Press, 2011.
- [2] B. B. Kadomtsev, *Tokamak Plasma: A Complex Physical System*. IOP Publishing, 1992.
- [3] C. M. Braams and P. E. Stott, *Nuclear Fusion: Half a Century of Magnetic Confinement Fusion Research*. IOP Publishing, 2002.
- [4] J. Wesson, *The Science of JET*. European Communities, 2000.
- [5] M. S. et al., “Progress in the iter physics basis chapter 1: Overview and summary,” *Nuclear Fusion*, vol. 47, no. 6, pp. S1–S17, 2007.
- [6] ITER Physics Expert Group, “Iter physics basis,” *Nuclear Fusion*, vol. 39, no. 12, pp. 2137–2174, 1999.
- [7] D. A. Ovsyannikov et al., “Program for scientific and educational investigations on the base of small spherical tokamak gutta,” in *IEEE PhysCon*, 2005.
- [8] J. Ramos et al., “Design of novillo tokamak,” *Nuclear Fusion*, vol. 29, no. 4, pp. 551–592, 1989.
- [9] D. B. Montgomery and R. J. Weggel, *Solenoid Magnet Design*. Robert E. Krieger Publishing Company, 1980.
- [10] F. C. Moon, *Magneto-Solid Mechanics*. John Wiley & Sons, 1984.
- [11] B. G. Hong, K. W. Lee, and S. K. Kim, “Tsc simulation of discharge in the kt-2 tokamak,” *Journal of the Korean Physical Society*, vol. 29, no. 1, pp. 44–51, 1996.
- [12] J. Hugill, “Tokamak operating limits,” *Nuclear Fusion*, vol. 23, no. 3, pp. 331–357, 1983.
- [13] F. F. Chen, *Introduction to Plasma Physics and Controlled Fusion*, 3rd ed. Springer, 2016.
- [14] F. Troyon, R. Gruber, H. Saurenmann, S. Semenzato, and S. Succi, “Mhd limits to plasma confinement,” *Plasma Physics and Controlled Fusion*, vol. 26, no. 1A, pp. 209–215, 1984.
- [15] J. P. Freidberg, *Plasma Physics and Fusion Energy*. Cambridge University Press, 2008.
- [16] A. J. L. Verhage, “Small tokamak design studies,” Eindhoven University of Technology, Tech. Rep., 1990.
- [17] A. Sykes, “Spherical tokamaks,” *Plasma Physics and Controlled Fusion*, vol. 39, no. 5A, pp. B247–B260, 1997.
- [18] Y. K. M. Peng and D. J. Strickler, “Features of spherical torus plasmas,” *Nuclear Fusion*, vol. 26, no. 6, pp. 769–777, 1986.
- [19] K. Miyamoto, *Plasma Physics and Controlled Nuclear Fusion*. Springer, 2005.
- [20] M. Greenwald, “Density limits in toroidal plasmas,” *Nuclear Fusion*, vol. 28, no. 12, pp. 2199–2207, 1988.
- [21] “Density limits in toroidal plasmas,” *Plasma Physics and Controlled Fusion*, vol. 44, no. 8, pp. R27–R80, 2002.
- [22] W. M. Stacey, *Fusion Plasma Physics*. Wiley-VCH, 2010.