M2 Erasmus mundus - Fusion-EP program

Microwave Pre-ignition in GOLEM Tokamak

Laboratory Work in GOLEM lab

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1 Introduction

1.1 Tokamak Plasma Breakdown and Pre-Ionization Challenges

In tokamak fusion devices, plasma initiation requires overcoming the electrical breakdown threshold of neutral gas through applied electric fields. For small tokamaks like GOLEM ($R_0 = 0.4$ m, minor radius $a = 0.085$ m), achieving plasma breakdown presents significant challenges due to limitations on operational parameters of the coils and optimal operating pressures (∼10 mPa). Pre-ionization techniques generate seed electrons before applying the main voltage. While GOLEM historically used an electron gun, recent studies demonstrate superior efficiency using **microwave (MW) pre-ionization** via electron cyclotron resonance (ECR). The following sections are based on previous studies:

1.2 Electron Cyclotron Resonance Fundamentals

ECR occurs when microwave energy matches electrons' natural rotation frequency in magnetic fields. The fundamental resonance condition is determined by:

$$f_C = \frac{eB}{2\pi m_e} \approx 2.8 \times 10^{10} B \quad [\mathrm{Hz} \cdot \mathrm{T}^{-1}] \tag{1}$$

For 2.45 GHz magnetrons (common household frequency), resonance occurs at 0.0875 T. Since GOLEM's toroidal field varies radially ($B = B_0 R_0 / R$), the resonance zone moves during operation, traversing from high-field to low-field regions in 7.4-8.8 ms. The following figure form a previous study demonstrates this phenomenon:

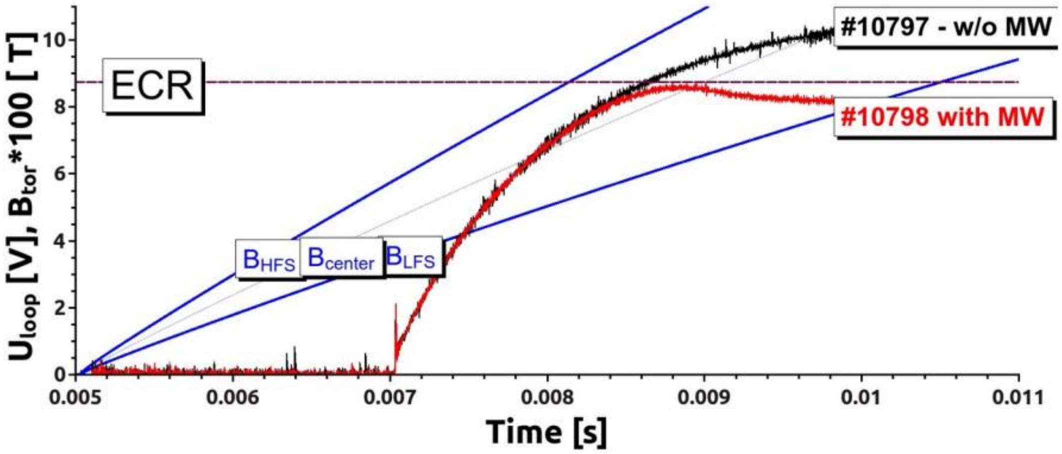

Figure 1: Characteristic shot of loop voltage in vacuum (black) and plasma (red). The magnetic fields (blue) at different positions inside the chamber are intersected by the line corresponding to ECR (purple), showing how resonance region moves from high field side (inside) to low field side (outside).

1.3 MW Pre-Ionization System in GOLEM

The experimental setup featured:

- 2.45 GHz magnetron (∼1 kW output)
- Rectangular waveguide injection
- Short pulses (<10 ms) during magnetic field ramp-up

Key operational parameters:

Parameter	Value
Frequency	2.45 GHz
Resonance field	0.0875 T
Gas pressure	10 mPa
Pulse duration	≤5 ms

1.4 Efficacy of MW Pre-Ionization

Experimental validation showed MW pre-ionization significantly reduces breakdown requirements:

- **Voltage reduction**: Up to 40% lower loop voltage compared to vacuum shots
- **Optimal timing**: Breakdown occurs precisely when ECR layer crosses vessel center ($B_t = 0.0875$ T)
- **Comparative advantage**: Outperforms electron gun when ECR layer inside vessel

This enhancement occurs because ECR heating creates seed electrons that facilitate gas ionization.

1.5 Plasma Characterization Studies

Researchers investigated plasma properties using **Langmuir probes** - diagnostic tools that measure electrical currents in plasma.

1.5.1 Experimental Approach

- A flat probe (5×5 mm) placed near plasma edge
- Voltage varied across shots (-20 V to +26.3 V)
- Current measurements during reproducible discharges
- Data analysis focused on plasma decay after MW switch-off

1.5.2 Key Findings

Measurements revealed fundamental plasma behaviors:

- **Plasma persistence**: Discharge continues ∼5 ms after MW turns off
- **Exponential decay**: Density and current decrease predictably ($\tau = 1.25$ ms)
- **Temperature stability**: Electron temperature remains constant (0.6–0.8 eV) post-heating
- **Density measurements**: Edge density $\sim 2.3 \times 10^{13}$ m^{-3} at peak

1.6 Diagnostic Challenges

The probe studies identified measurement complexities:

- **Data reproducibility**: Some voltage points showed irregular readings
- **Current anomalies**: Ion current increased with probe voltage unexpectedly
- **Electron collection**: Magnetic fields hindered electron measurements

These findings highlighted needs for improved diagnostics in future experiments.

1.7 Conclusions from Previous Studies

MW pre-ionization in GOLEM demonstrates:

1. Significant loop voltage reduction (∼40% at optimal conditions)
2. Effective plasma initiation when ECR zone traverses vessel
   item Plasma persistence with predictable decay after MW switch-off
3. Edge plasma parameters consistent with small tokamaks

These results establish MW pre-ionization as a superior alternative to electron guns for GOLEM operations, while revealing opportunities for improved plasma diagnostics during ECR-assisted breakdown.

2 Experimental Setup

2.1 Microwave Pre-Ionization System

The microwave pre-ionization system for GOLEM tokamak employs a commercial 2.45 GHz magnetron as its core component. This frequency was selected due to the commercial availability of components and the direct match with GOLEM's operational magnetic field requirements (0.0875 T). Figure 2 illustrates the complete implementation showing the magnetron, waveguide assembly, and vacuum vessel interface.

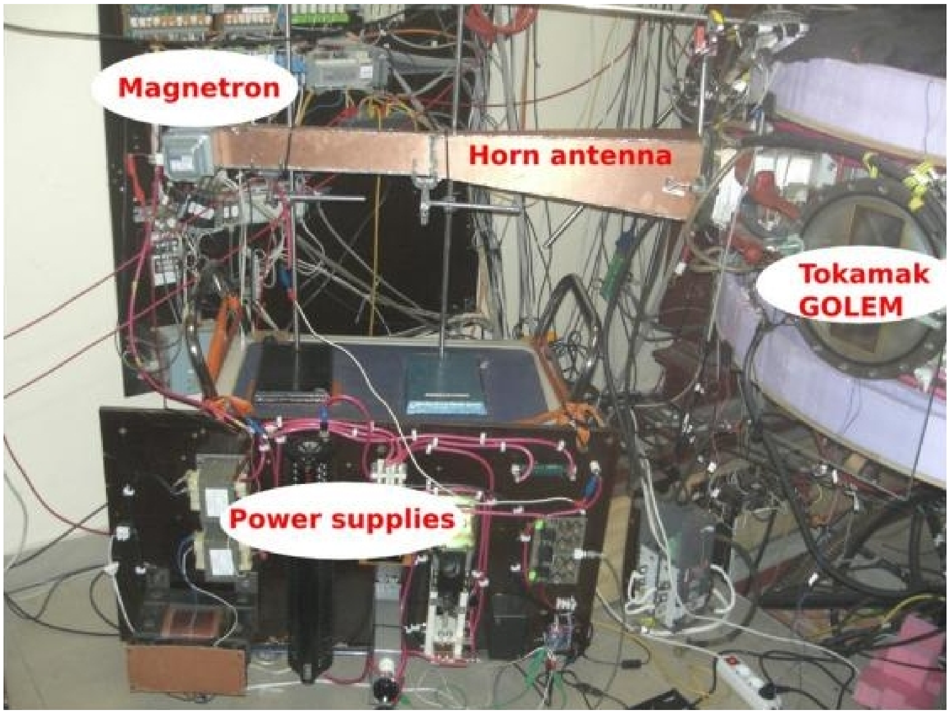

Figure 2: Complete microwave pre-ionization system implementation on GOLEM tokamak showing the magnetron, the waveguide transition section, and power supply.

2.2 Magnetron Power Supply Configuration

A custom power supply system was designed to meet the magnetron's specialized operational requirements:

- **Two-stage transformer design**:
    1. First transformer provides near-threshold voltage (3.2 kV) to initiate electron emission
    2. Second transformer delivers pulsed high voltage (4.1 kV) to drive magnetron into full operation
- **Precision timing**: Trigger pulse provided by optically isolated mechanism which can be synchronized to the toroidal field.
- **Pulse control**: Variable pulse width with short pulse capabilities of up to a few milliseconds.

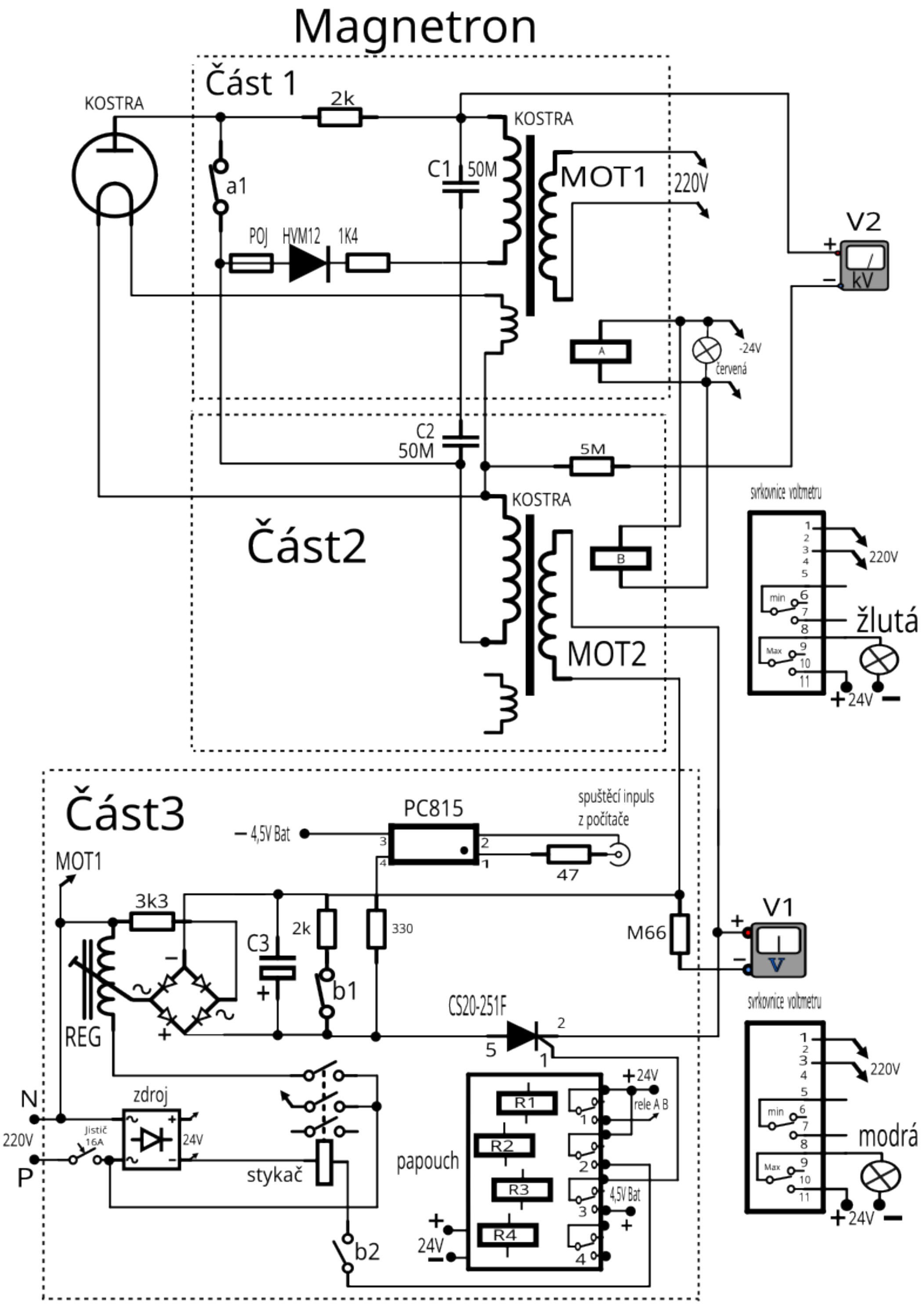

Figure 3: Electrical schematic of custom magnetron power supply showing dual-transformer design and trigger synchronization circuit.

2.3 Waveguide Implementation Challenges

The initial waveguide configuration used a tapered rectangular waveguide to connect the magnetron output to the vacuum vessel:

- **Geometry limitations**: Rectangular waveguide required tapering to match vessel port dimensions
- **Electric field reduction**: Expansion of the taper causes reduction in electric field intensity.
- **Bulkiness**: Overall bulk of assembly creates spatial constraints

2.4 Vessel Interface Design

The GOLEM vacuum vessel features dedicated radial ports suitable for microwave coupling. Figure 4 shows the mechanical design with key dimensions:

- **Port locations**: Two opposing radial ports, one upper and other lower.
- **Port diameter**: 199 mm standard flange
- **Distance to plasma**: 230 mm from port entrance to plasma edge

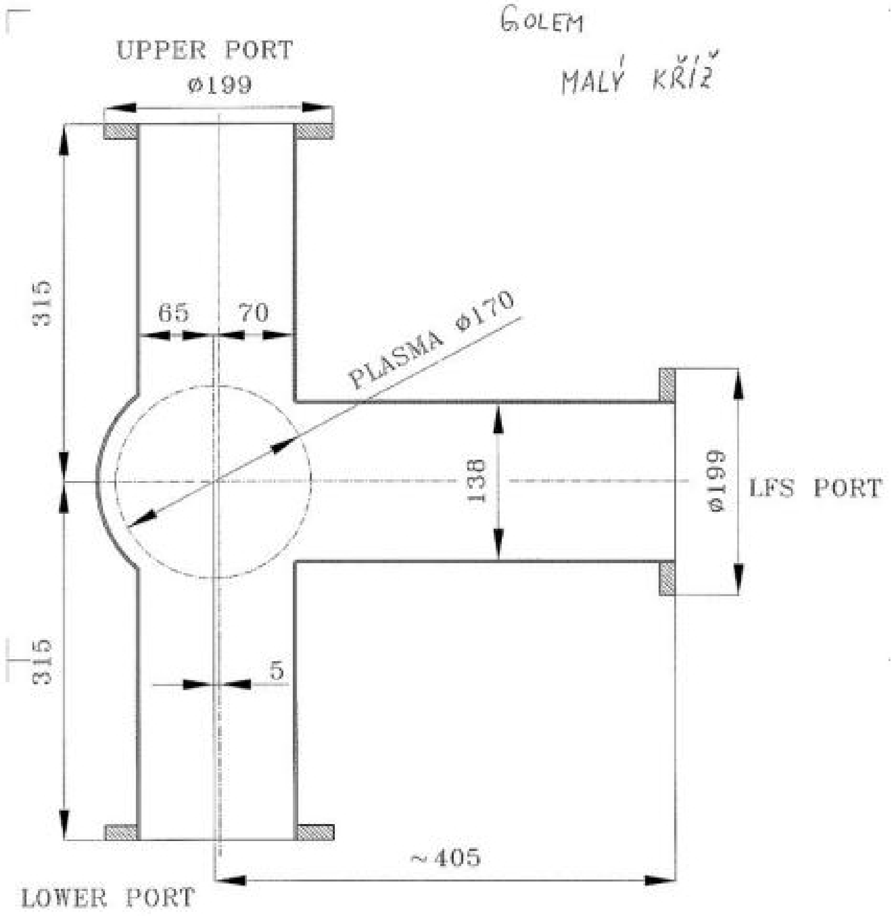

Figure 4: GOLEM vacuum vessel port mechanical diagram.

2.5 Circular Waveguide Solution

To address rectangular waveguide limitations, the concept of using the vessel port as a circular waveguide was theorized:

- **Direct port coupling**: Eliminates tapering by matching port diameter
- **Field preservation**: Circular cross-section maintains field intensity (Fig. 5)
- **Compact design**: Major size reduction compared to rectangular system

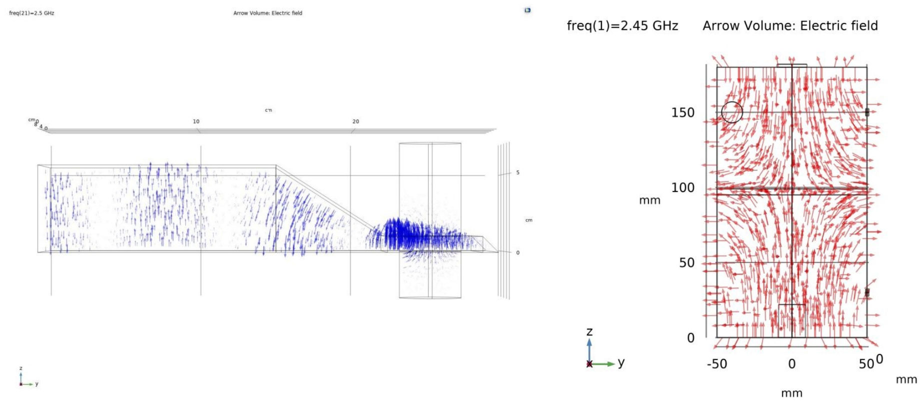

Figure 5: Electric field distribution comparison: (Left) Rectangular waveguide showing electric fields with contracting taper, (Right) Circular waveguide maintaining field uniformity. This figure acts as an example. In actuality, the taper expands in the rectangular waveguide, thus having opposite effect of as shown in the figure.

2.6 System Verification Protocol

Before tokamak integration, the microwave system underwent a comprehensive validation:

1. **Power supply testing**: High-voltage output verification using voltmeters
2. **Control System testing**: Verification of the lan-based control circuit
3. **Microwave Radiation Verification**: Florescent tube used as dummy load and an oscilloscope used with coupling coil to verify the production of microwaves.

3 Results and Discussion

3.1 Power Supply Control Mechanism

The power supply's operation relies on a precisely coordinated relay system implemented through a control daughter-board. This board contains four relays, with three actively utilized in the current configuration. Figure 6 shows the physical implementation of this critical control system.

Relay 1 serves as the primary safety interlock, simultaneously controlling two high-power relays within the main power supply. These high-power relays are positioned across the capacitor bank and the combined high-voltage output (threshold transformer and pulse transformer). In the default OFF/LOW state, these relays remain closed, creating a short circuit across both the capacitor bank and high-voltage output terminals. This design ensures complete discharge of stored energy when the system is inactive, providing essential protection against residual voltage hazards.

Relay 2 manages the primary power distribution to the system. When pushed ON/HIGH, it connects the mains input to both the capacitor bank charging circuit and the primary winding of the threshold transformer. The threshold transformer generates two critical outputs: the high-voltage bias (approximately 3.2 kV) required to bring the magnetron near its emission threshold, and the heater voltage that preconditions the magnetron's cathode.

Relay 3 governs the precise triggering mechanism through a silicon-controlled rectifier (SCR). When low, this relay completely isolates the SCR's gate terminal. Upon activation, it connects the SCR gate to a dedicated battery's positive terminal. The actual triggering occurs when an external pulse signal connects the SCR anode to the battery's negative terminal, completing the circuit and allowing the capacitor bank to discharge through the pulse transformer's primary winding. This discharge generates the high-voltage pulse that drives the magnetron into full microwave emission.

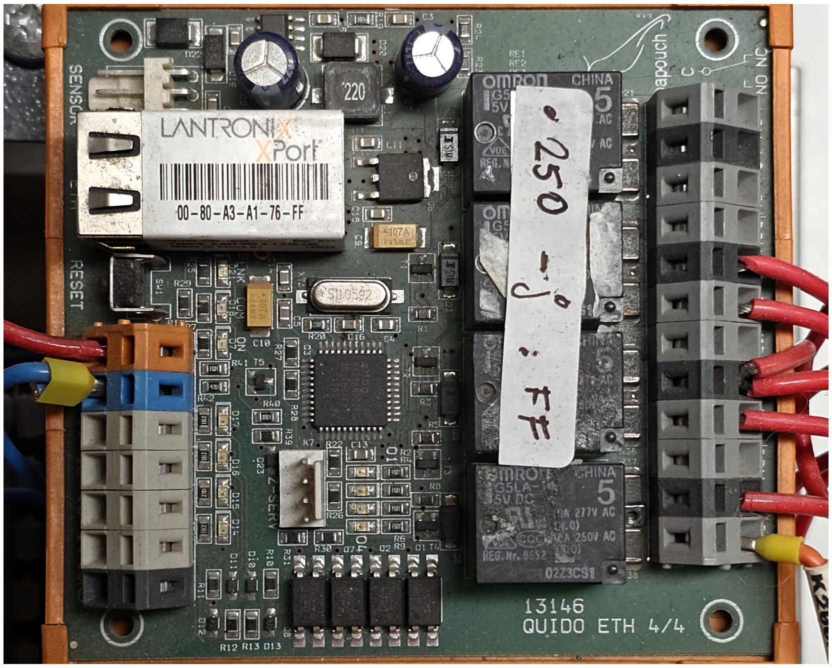

Figure 6: Control daughter-board showing relay arrangement from bottom to top: Relay 1 (safety interlock), Relay 2 (main power control), Relay 3 (SCR trigger gate).

3.2 Diagnostic Instrumentation

To verify system operation, comprehensive monitoring instruments were implemented across critical nodes. Figure 7 illustrates the microwave detection apparatus. Voltmeters were installed across both the capacitor bank and the power supply's high-voltage output terminals to monitor charging behavior and output characteristics during operation.

A dummy load assembly was developed using a fluorescent light ring positioned in contact with the magnetron's output stub. This arrangement serves dual purposes: it safely absorbs microwave energy during testing, while the visible fluorescence provides immediate visual confirmation of microwave generation.

Microwave emission was quantitatively verified using a radio-frequency (RF) pickup coil positioned near the magnetron. This simple detector consists of a wire loop coupled to a diode, converting radiated microwave energy into a measurable DC signal. The output from this sensor was connected to an oscilloscope, enabling visualization of microwave pulse timing and relative power levels.

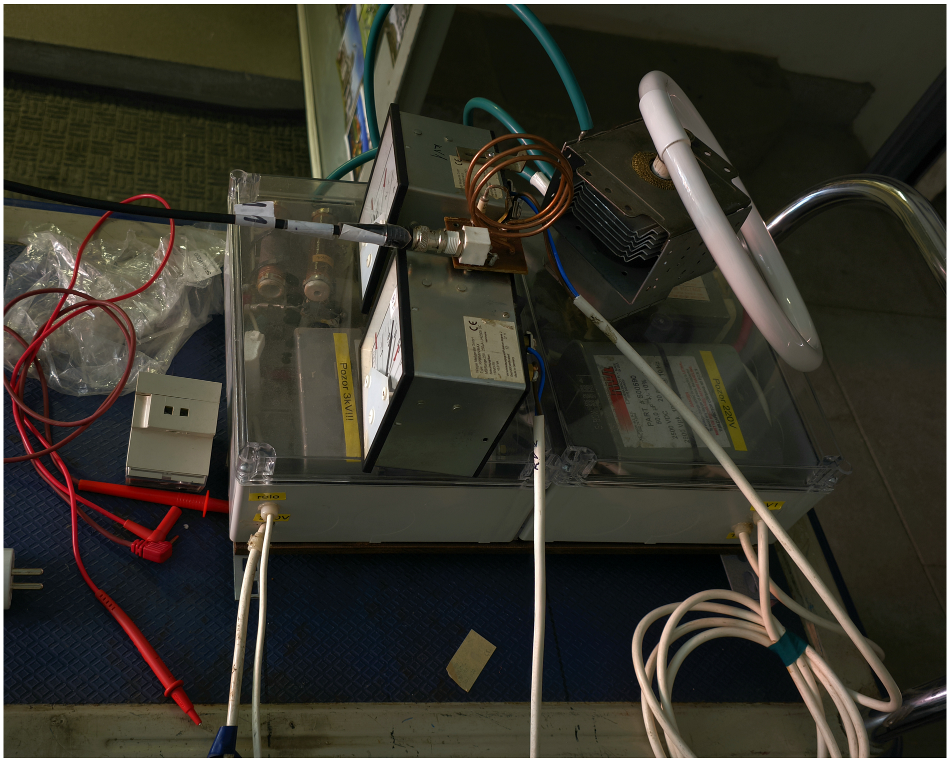

Figure 7: Detection loop (brown copper coil) near magnetron, Fluorescent ring to provide visual emission confirmation and voltmeters besides them.

3.3 Triggering System Architecture

The trigger pulse generation uses a layered isolation approach for safety and noise immunity. As shown in Figure 8, an Arduino micro-controller generates the primary trigger signal based on pre-programmed timing sequences. This low-voltage signal first passes through an external optical isolator before reaching the power supply's trigger input, which also uses optical isolation internally.

The trigger signal is simultaneously routed to an oscilloscope channel, enabling direct comparison between command timing and actual microwave output. This dual-isolation design ensures complete galvanic separation between control electronics and high-voltage components while providing precise timing control.

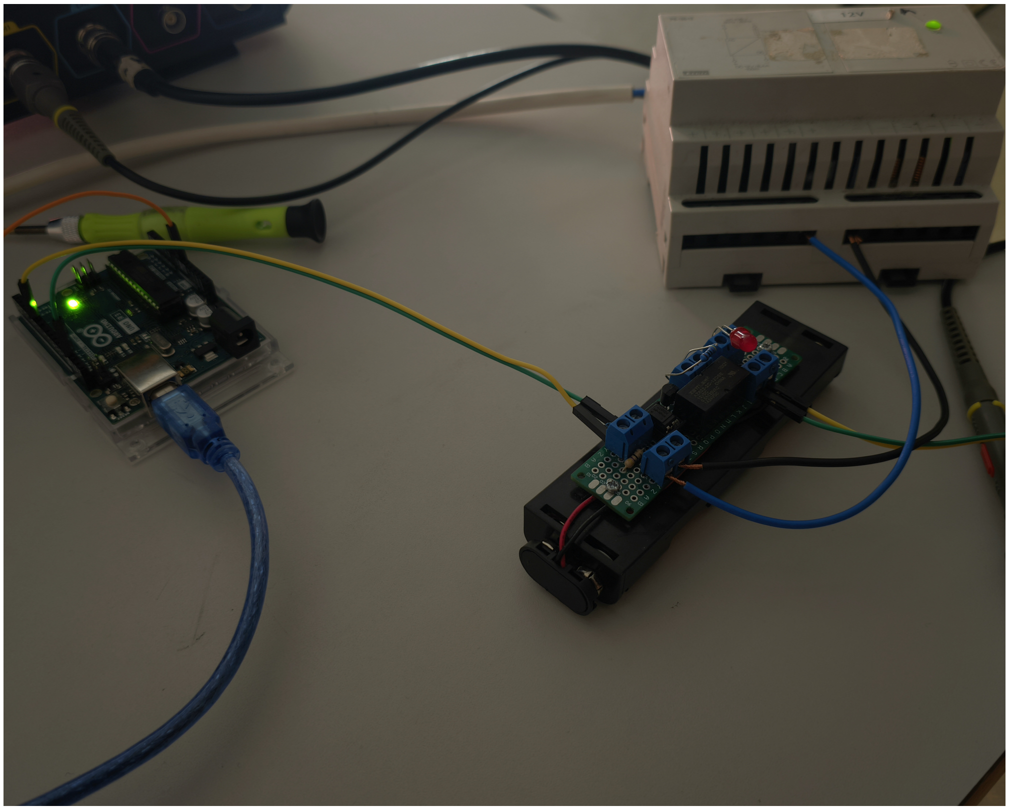

Figure 8: Trigger system architecture consisting of an Arduino controller and External optical isolator.

3.4 Automated Control Framework

Operational automation was achieved through an integrated software framework running on the tokamak's control computer. Figure 9 shows the complete test configuration. The control process initiates with a bash script that accepts pulse timing parameters (duration, delay, etc.) and writes these into an Arduino program template (main.txt).

The script subsequently establishes an SSH connection to the tokamak control computer, sending telnet commands to activate the daughter-board relays in strict sequence: Relay 1 → Relay 2 → Relay 3. Following relay activation, a helper script compiles and uploads the customized Arduino program, initiating the trigger sequence that generates the microwave pulse.

Post-pulse, the control system executes a reverse relay deactivation sequence: Relay 3 → Relay 2 → Relay 1. This systematic approach ensures safe power supply reset. A virtual trigger mode allows complete procedure testing without physical hardware, facilitating code development and timing optimization.

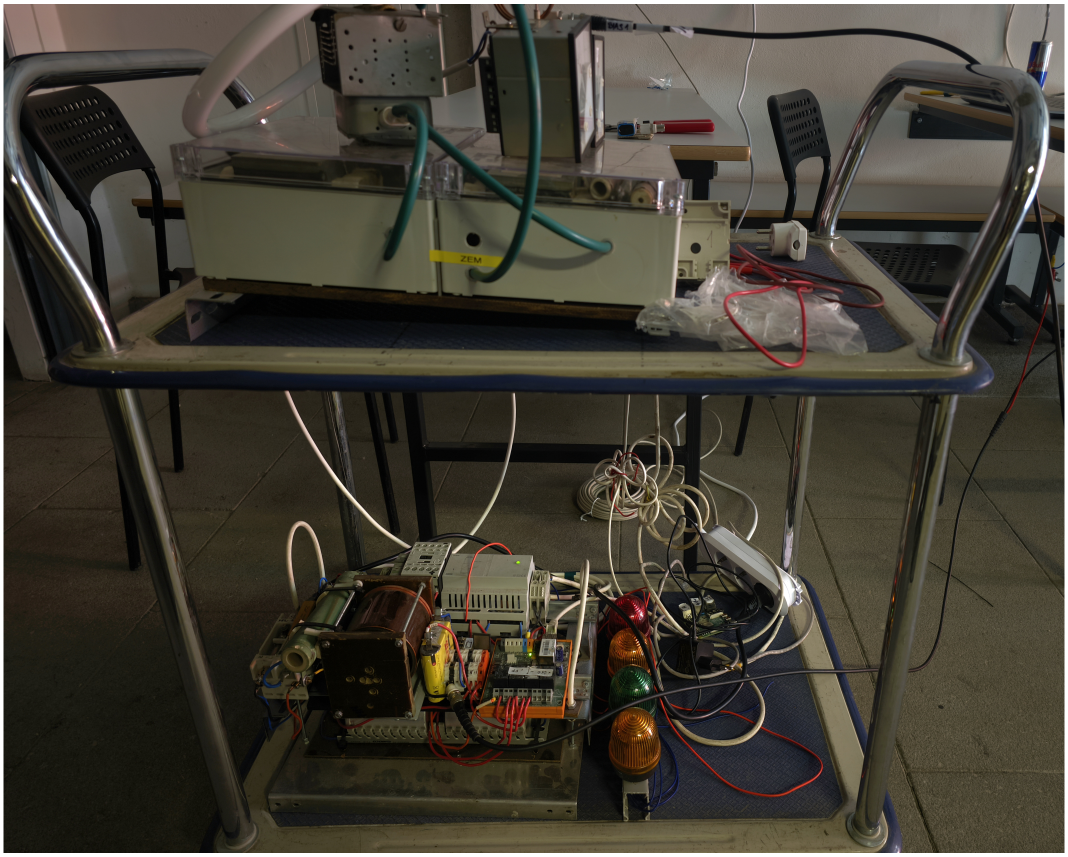

Figure 9: Complete power supply.

3.5 Verification Results

System functionality was confirmed through synchronized oscilloscope measurements comparing trigger commands with microwave output. Figure 10 presents representative results from validation testing.

The upper yellow trace consistently shows the trigger pulse generated by the Arduino controller captured after the isolation circuit, which shows consistent alignment with the programmed timing parameters. The lower blue trace demonstrates the corresponding microwave power emission detected by the RF pickup coil, with pulse onset occurring within 200 μs of trigger activation.

Successful operation was further confirmed by the fluorescent dummy load's immediate illumination during pulse delivery and voltage measurements confirming capacitor bank charging and proper high-voltage generation. These verification tests confirm that the power supply reliably produces microwave pulses with controllable timing characteristics suitable for tokamak pre-ionization experiments.

Figure 10: Synchronized oscilloscope measurements: (a) Double pulse in microwave power and (b) Decaying pulse of microwave power. Both show trigger pulse (upper yellow trace) and microwave power output (lower blue trace). The trigger pulse duration is 5 ms.

4 Conclusion and Future Work

The microwave power supply system was successfully tested and verified as operational. Microwave generation was confirmed through oscilloscope measurements

4.1 Observed Challenges

During testing, unexpected microwave output patterns were observed including double pulsing, where extra pulses appeared after the main pulse ended and prolonged output, where microwaves continued after the pulse should have stopped. These issues likely arise from the magnetron heating up during operation. Reducing the heater power may help solve this problem by stabilizing electron flow within the device. Providing active cooling to the magnetron might also be a possible solution.

4.2 Needed Improvements

Before connecting to the tokamak, several hardware repairs should be implemented. Old resistors should be replaced, critical solder connections require reinforcement, and internal wiring could be reorganized for easier maintenance. These practical improvements will enhance system reliability during repeated operation cycles and ensure safer integration with the tokamak.

4.3 Future Steps

The immediate plan involves physically connecting the system to the GOLEM tokamak. This includes attaching the magnetron to the vacuum chamber ports, verifying proper function under vacuum conditions, testing performance in magnetic fields, and conducting plasma initiation trials using microwave pre-ionization.

5 Appendix

5.1 Power Supply Control Script

This Bash script automates the power supply testing procedure, handling SSH connections to the remote host, relay sequencing, and Arduino programming.

Listing 1: Power control script (auto_relay.sh)

```
#!/bin/bash

# Check if required parameters are provided
if [ $# -lt 4 ]; then
    echo "Usage: $0 <remote_host> <username> <password> <pulse_duration_ms>"
    echo "Example: $0 remote.example.com myuser mypass 2000"
    exit 1
fi

REMOTE_HOST=$1
USERNAME=$2
PASSWORD=$3
DURATION=$4

# Check if sshpass is available
if ! command -v sshpass &> /dev/null; then
    echo "Error: sshpass is required. Install it with ’sudo apt install sshpass’"
    exit 1
fi

# Check remote device connection via SSH
virtual_mode=false
echo "Checking remote device connection..."
if ! sshpass -p "$PASSWORD" ssh -o StrictHostKeyChecking=no -o ConnectTimeout=2 "$USERNA
    "timeout 1 bash -c ’echo > /dev/tcp/192.168.2.250/10001’"; then
    echo "WARNING: No device found on remote host - using virtual relay mode"
    virtual_mode=true
fi

# Function to set a switch to HIGH or LOW on remote server
set_switch() {
    local switch=$1
    local state=$2
    if [ "$virtual_mode" = true ]; then
        echo "VIRTUAL: Switch $switch set to $state"
    else
        echo "Setting switch $switch to $state on remote host"
        sshpass -p "$PASSWORD" ssh "$USERNAME@$REMOTE_HOST" <<EOF
timeout 1 telnet 192.168.2.250 10001 <<EOT
*B1OS${switch}${state}*
EOT
EOF
    fi
}

# Exit handler to ensure all switches are off when the script ends
function cleanup {
    echo "Resetting all switches..."
```

```
    if [ "$virtual_mode" = false ]; then
        set_switch 3 L
        set_switch 2 L
        set_switch 1 L
    fi
    echo "Exiting..."
}
trap cleanup EXIT

# Modify pulse duration in pulse.ino
sed -i "s/int pulseDuration = [0-9]\+;/int pulseDuration = $DURATION;/g" pulse.ino

# Set relays HIGH in sequence
set_switch 1 H
sleep 0.1
set_switch 2 H
sleep 0.1
set_switch 3 H
sleep 5
# Upload the code
./upload.sh

# Wait for pulse duration
sleep $(echo "$DURATION/1000" | bc -l)
sleep 1
# Set relays LOW in reverse sequence
set_switch 3 L
sleep 0.1
set_switch 2 L
sleep 0.1
set_switch 1 L

echo "Pulse sequence completed successfully"
```

5.2 Arduino Uploader Script

This helper script compiles and uploads the Arduino code to the micro-controller during the test sequence.

Listing 2: Arduino upload script (upload.sh)

```
#!/bin/bash

ARDUINO_CLI="$(dirname "$0")/arduino-ide_2.3.6_Linux_64bit/resources/app/lib/backend/res
[ -f "$ARDUINO_CLI" ] || { echo "Error: arduino-cli not found"; exit 1; }

TEMP_DIR="/tmp/pulse_$$"
mkdir -p "$TEMP_DIR/pulse" && cp "$(dirname "$0")/pulse.ino" "$TEMP_DIR/pulse/pulse.ino"

"$ARDUINO_CLI" compile --fqbn arduino:avr:uno "$TEMP_DIR/pulse" && \
sudo "$ARDUINO_CLI" upload -p /dev/ttyACM0 --fqbn arduino:avr:uno \
--input-dir "$(ls -td "$HOME/.cache/arduino/sketches/"* | head -1)" pulse*

rm -rf "$TEMP_DIR"
```