Development of a 45-kV Pulse Transformer for a 1.5-MW Magnetron Application*

S. D. Jang, Y. G. Son, J. S. Oh
Pohang Accelerator Laboratory
Pohang University of Science and Technology (POSTECH)

Pohang University of Science and Technology (POSTECH)

San 31, Hyoja-dong, Pohang,
Kyungbuk 790-784, S. KOREA

* This work is partially supported by KBSI and KSTAR project by MOST.
**Introduction**

Microwave heating system of KSTAR consists of ECH and LHCD. ECH and LHCD offer the reliability of operation in the beginning of plasma formation and non-inductive current drive for long time steady state operation, respectively. LHCD demands C-band microwave system with a frequency of 5 GHz. A pulse generator with a power of 3.6 MW, 4 \( \mu s \), 200 pps is required to drive a high-power magnetron. The pulse transformer producing a pulse with a peak voltage of 45 kV is required to produce a 5-GHz microwave source in a 1.5-MW magnetron. We have designed the high power pulse transformer with 1:4 step-up turns ratio. The peak power handling capability is 3.6-MW (45 kV, 90 A at load side with 4 \( \mu s \) pulse width). In this paper, the results of the high power pulse transformer design and performance characteristics are presented.

* This work is partially supported by POSCON and KSTAR project by MOST.
Simplified Equivalent Circuit

**Pulse Generator**
- \( V_G \): Charging Voltage of Storage Capacitor
- \( S_G \): Thyristor Switch
- \( R_G \): Primary Impedance
- \( L_W \): Wiring Inductance

**Pulse Transformer**
- \( L_L \): Leakage Inductance
- \( R_E \): Core Resistance
- \( L_P \): Primary Inductance
- \( C_D \): Distributed Capacitance

**Load**
- \( C_{load} \): Load Capacitance
- \( R_L \): Load Impedance
Wave Shape Definitions

Overshoot: \( C_D, L_L, \gamma \)

Source Voltage

Droop: \( L_p, R_L, \tau_p \)
\[ D = R_L \frac{\tau_w}{2 L_p} \]
\[ L_p = 4\pi \mu_e N_p^2 A_e / L_m \text{ [nH]} \]

Load Voltage

Return backswing: \( C_D, L_L, \) Impedance mismatch

Rise time \( T_r : C_D, L_L \)
\[ T_r = \sqrt{2\pi S(\sigma)} \sqrt{L_T C_T} \]

Fall time

Backswing: \( C_D, L_E, R_L, R_E \)
Normalized Rising Pulse Waveform
Design Parameters of the 1:4 Pulse Transformer

**Given parameters (Requirements)**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Designed</th>
</tr>
</thead>
<tbody>
<tr>
<td>peak load voltage (kV)</td>
<td>40 (negative)</td>
</tr>
<tr>
<td>Peak load current (A)</td>
<td>96 (max)</td>
</tr>
<tr>
<td>Load resistance (Ohms)</td>
<td>470 (Secondary)</td>
</tr>
<tr>
<td>Primary RMS current (A)</td>
<td>26.93 (max)</td>
</tr>
<tr>
<td>Secondary RMS current (A)</td>
<td>6.73 (max)</td>
</tr>
<tr>
<td>Pulse width (µs)</td>
<td>4</td>
</tr>
<tr>
<td>Turns ratio</td>
<td>1:4</td>
</tr>
<tr>
<td>Pulse repetition rate</td>
<td>200 pps</td>
</tr>
<tr>
<td>Load capacitance</td>
<td>31.4 pF</td>
</tr>
</tbody>
</table>

**Designed parameters (Results)**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Designed</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turns ratio</td>
<td>4</td>
<td>3.87</td>
</tr>
<tr>
<td>Primary turns</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>Leakage inductance (µH)</td>
<td>37</td>
<td>42.2</td>
</tr>
<tr>
<td>Distributed capacitance (pF)</td>
<td>12.8</td>
<td>38.7</td>
</tr>
<tr>
<td>primary inductance (mH)</td>
<td>21.6</td>
<td>19.85 (LCR)</td>
</tr>
<tr>
<td>Core material thickness (µm)</td>
<td>50</td>
<td>-</td>
</tr>
<tr>
<td>Magnetic flux swing (T)</td>
<td>0.68</td>
<td>-</td>
</tr>
<tr>
<td>Effective permeability</td>
<td>800</td>
<td>803</td>
</tr>
<tr>
<td>Gap length (µm)</td>
<td>24</td>
<td>-</td>
</tr>
<tr>
<td>Effective core cross-section (cm²)</td>
<td>66</td>
<td>-</td>
</tr>
<tr>
<td>Mean magnetic path length (cm)</td>
<td>50.3</td>
<td>-</td>
</tr>
<tr>
<td>Core weight (kg)</td>
<td>47</td>
<td>-</td>
</tr>
</tbody>
</table>
Design of Pulse Transformer(1:4) for 1.5 MW Magnetron

Primary winding:
- 10 turns with 2 parallel on each leg
- $x \Phi 1.6 \times 4.15$ Space ($l_c : 83$)

$A_o = 75 \text{ Cm}^2 (25 \times 3)$
$A_e = 66 \text{ Cm}^2 (22 \times 3)$
$L_m = 50.3 \text{ Cm}$
$\Delta 01 = 8, \Delta 12 = 10,$
$\Delta 23 = 10, \text{corona gap}=9$
$N_s : 40 \text{ turns}$
Corona ring : all secondary winding end point (dia. 5)

unit : mm

Secondary winding I:
- 40 turns $x \Phi 1.8 \times 2$ Space ($l_c : 78$), $78 + 15 + 7 = 100$

Secondary winding II:
- 10 turns $x \Phi 1.8$
- $x 3$ Space ($l_c : 27$)

Designed by S.D. Jang
October 30, 2003
Coil Geometry and Winding Configuration

Core (50x50.4)

Primary winding

Secondary winding

Isolated and bifilar winding (1:4)

\[ a = 181 \]
\[ b = 66 \]
\[ l_c = 78 \]
\[ \Delta 12 = 10 \]
## Specification and Electrical Parameters of Pulse Transformer

### Design Parameters of Modulator

<table>
<thead>
<tr>
<th>Item</th>
<th>Model calculated Value</th>
<th>Measured Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Inductance [mH]</td>
<td>1.271</td>
<td>1.268</td>
</tr>
<tr>
<td>Secondary Inductance [mH]</td>
<td>20.342</td>
<td>19.85</td>
</tr>
<tr>
<td>Leakage Inductance [µH]</td>
<td>79.3</td>
<td>42.2</td>
</tr>
<tr>
<td>Distributed Capacitance [pF]</td>
<td>44.2</td>
<td>38.7</td>
</tr>
</tbody>
</table>

### Pulse Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Voltage [kV]</td>
<td>45</td>
</tr>
<tr>
<td>Peak Current [A]</td>
<td>96</td>
</tr>
<tr>
<td>Load Impedance [Ω]</td>
<td>470</td>
</tr>
<tr>
<td>HV Pulse Length [µs]</td>
<td>4</td>
</tr>
<tr>
<td>Pulse Energy [J]</td>
<td>17.3</td>
</tr>
<tr>
<td>Repetition Rate Max [Hz]</td>
<td>200</td>
</tr>
<tr>
<td>Step-up Ratio</td>
<td>4</td>
</tr>
<tr>
<td>PFN Charging Voltage [kV]</td>
<td>25</td>
</tr>
<tr>
<td>PFN Impedance [Ω]</td>
<td>29.37</td>
</tr>
<tr>
<td>PFN Section Cap [nF]</td>
<td>10</td>
</tr>
<tr>
<td>PFN Section Inductance [µH]</td>
<td>8.63</td>
</tr>
<tr>
<td>PFN Section Number</td>
<td>7</td>
</tr>
<tr>
<td>Charging Resistance [Ω]</td>
<td>100</td>
</tr>
<tr>
<td>Thyratron (CX1191D)</td>
<td>8 MW, 35 kV, 500 A,</td>
</tr>
<tr>
<td>Peak Voltage [kV]</td>
<td>45</td>
</tr>
<tr>
<td>Peak Current [A]</td>
<td>96</td>
</tr>
<tr>
<td>Load Impedance [Ω]</td>
<td>470</td>
</tr>
<tr>
<td>HV Pulse Length [µs]</td>
<td>4</td>
</tr>
<tr>
<td>Pulse Energy [J]</td>
<td>17.3</td>
</tr>
<tr>
<td>Repetition Rate Max [Hz]</td>
<td>200</td>
</tr>
<tr>
<td>Step-up Ratio</td>
<td>4</td>
</tr>
<tr>
<td>PFN Charging Voltage [kV]</td>
<td>25</td>
</tr>
<tr>
<td>PFN Impedance [Ω]</td>
<td>29.37</td>
</tr>
<tr>
<td>PFN Section Cap [nF]</td>
<td>10</td>
</tr>
<tr>
<td>PFN Section Inductance [µH]</td>
<td>8.63</td>
</tr>
<tr>
<td>PFN Section Number</td>
<td>7</td>
</tr>
<tr>
<td>Charging Resistance [Ω]</td>
<td>100</td>
</tr>
<tr>
<td>Thyratron (CX1191D)</td>
<td>8 MW, 35 kV, 500 A,</td>
</tr>
</tbody>
</table>
Parameters of Pulse Transformer

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total magnetic flux density swing [T]</td>
<td>0.68</td>
</tr>
<tr>
<td>Effective magnetic Permeability</td>
<td>800</td>
</tr>
<tr>
<td>Core Packing factor [%]</td>
<td>0.88</td>
</tr>
<tr>
<td>Magnetic Cross section Area [cm²]</td>
<td>66</td>
</tr>
<tr>
<td>Mean Magnetic Path Length [cm]</td>
<td>50.3</td>
</tr>
<tr>
<td>Distance between layers [cm]</td>
<td>1</td>
</tr>
<tr>
<td>Winding length [cm]</td>
<td>7.5</td>
</tr>
<tr>
<td>Mean circumference between layers [cm]</td>
<td>28.7</td>
</tr>
<tr>
<td>Primary Turn Number</td>
<td>10</td>
</tr>
<tr>
<td>Secondary Turn Number</td>
<td>40</td>
</tr>
</tbody>
</table>

\[
T_r = \frac{2\pi \sqrt{L_L \cdot C_D}}{4}
\]

\[
L_L = \frac{\mu_0 \Delta \cdot u \cdot N_s^2}{l_c}
\]

\[
C_D = \frac{\varepsilon_0 \varepsilon_r \cdot l_c}{\Delta} \left( \frac{n-1}{n} \right)^2
\]

\[
T_r = \frac{\pi}{2c} \sqrt{\varepsilon_r \cdot N_s \cdot u \cdot n-1}
\]

\[
\tau : \text{Pulse Width}
\]

\[
V_s : \text{Secondary Voltage}
\]
Circuit Diagram of Modulator

**Pulse Modulator**
- Peak Power: 3.6 MW
- Charging Voltage: 22.5 kV
- PFN Output Voltage: 11.25 kV
- PFN Output Current: 382 A
- HV Pulse Width (70% Voltage): 4.0 µs
- Repetition Rate: 200 pps

**C-Band 1.5MW Magnetron**
- Frequency: 5100 MHz
- Output Power: 1.5 MW
- Repetition Rate: 200 pps
- Efficiency: 52%
- Beam Voltage: 39 kV
- Beam Current: 83 A
- RF Pulse Width: 4.0 µs

**Dong-A 403**
- Output Voltage: 25 kV
- Charging Rate:
  - Peak: 5 kJ/s
  - Average: 4.0 kJ/s

**High Voltage Switched Mode Power Supply**
- Dong-A 403
- Output Voltage: 25 kV
- Charging Rate:
  - Peak: 5 kJ/s
  - Average: 4.0 kJ/s

**Magnetron Pulse Transformer**
- Tank Frequency: 5100 MHz
- Output Power: 1.5 MW
- Repetition Rate: 200 pps
- Efficiency: 52%
- Beam Voltage: 39 kV
- Beam Current: 83 A
- RF Pulse Width: 4.0 µs
Air cooled magnetron
- SFD369
- Frequency: 4.9 – 5.1GHz
- Peak power output: 1.5MW
- Duty Cycle: 0.001 (1 kHz repetition)
- Peak Anode Voltage Max: 40.5 kV
- Peak Anode Current Max: 90 Amps
- Pulse Width: 0.4~1.4 µs

WR187 w/g components
- Straight waveguide
- E-bend
- H-bend
- Dual directional coupler
- 4-port circulator

Interactive Image Regions:
- Interlock signals
  - Reflection power > 50%
  - Arc signal (in waveguide)
  - SF6 gas pressure < 30 psig
  - Magnetron cooling fan off

Control Unit
- PLC / pulse gen.

Inverter Powersupply

Thyratron Switch / PFN

Pulse Transformer

19” rack

PFN Pulse Modulator
(Max 45 kV, 96 A, 4 µs)

Trigger pulse (Internal & External DG535)
Interlock signals (Contact Closures)
RS232 comm port (for remote control)

5.0-GHz magnetron
Dry dummy load
Dual directional coupler
E-bend or H-bend
Optical cable
4-port circulator
Dry Dummy Load
Arc detector
Pressure Gauge / Valve
FAN
Heater
DC 5 V
28 A

WR187 w/g components:
- Straight waveguide
- E-bend
- H-bend
- Dual directional coupler
- 4-port circulator

SF6

SFD369
- Frequency: 4.9 – 5.1GHz
- Peak power output: 1.5MW
- Duty Cycle: 0.001 (1 kHz repetition)
- Peak Anode Voltage Max: 40.5 kV
- Peak Anode Current Max: 90 Amps
- Pulse Width: 0.4~1.4 µs

KAPRA 2004, Cheorwon Cityhall, Gangwon (July 9-10)
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anode Voltage (kV)</td>
<td>39</td>
</tr>
<tr>
<td>Anode Current (A)</td>
<td>83</td>
</tr>
<tr>
<td>Magnetron Impedance (Ω)</td>
<td>470</td>
</tr>
<tr>
<td>Pulse Width (µs)</td>
<td>4</td>
</tr>
<tr>
<td>Average Output Power (kW)</td>
<td>1.65</td>
</tr>
<tr>
<td>Peak Output Power (MW)</td>
<td>1.68</td>
</tr>
<tr>
<td>Duty</td>
<td>0.0008</td>
</tr>
<tr>
<td>Heater V, I (V, A)</td>
<td>5, 28</td>
</tr>
<tr>
<td>Frequency (MHz)</td>
<td>4900-5100</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>52</td>
</tr>
</tbody>
</table>
Photographs for LHCD Test System

PFN & HV Box

Modulator Test Setup

KAPRA 2004, Cheorwon Cityhall, Gangwon (July 9-10)
Test and Simulation Results

- Time
- \(5.008\text{ms}\)
- \(5.010\text{ms}\)
- \(5.012\text{ms}\)
- \(5.014\text{ms}\)
- \(5.016\text{ms}\)
- \(5.018\text{ms}\)

- \(-100\text{A}\)
- \(-50\text{A}\)
- \(0\text{A}\)
- \(140\text{A}\)

- \(-45\text{kV}\)
- \(-97\text{A}\)

- Rise time: 0.4 \(\mu\)s
- Flatness: 1.8%
- Flattop Pulse width: 2.8 \(\mu\)s
Summary & Future Plan

• Summary

1. Equivalent circuit analysis of the pulse transformer.
2. Normalized rising waveform as function of the damping factor.
3. Design of the 1:4 pulse transformer for a microwave tube.
4. Establishment of the general design procedure, equation for high-power pulse transformer.
5. Waveform analysis for simulation circuit of the pulse system.
6. Measurement of equivalent circuit parameters for transformer

• Future plan

1. Measurement of pulse characteristics according to specification.
2. HV performance test by using a 5 GHz, 1.6 MW magnetron load for a LHCD system.
3. Optimum design and fabrication for high efficiency.