Design, Manufacturing, and Performance Results of a 1.2 MW Peak, 704 MHz Multibeam Inductive Output Tube

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Outline

▌ Multi-Beam Inductive Output Tube (MB-IOT) for European Spallation Source (ESS)

▌ MB-IOT Requirement

▌ Main Design Features

▌ Manufacturing Overview

▌ Test Results

▌ Summary
MB-IOT for European Spallation Source ESS

- 2 GeV - 62.5 mA (14Hz) proton linac to produce neutrons from Tungsten target
  - Average Beam Power 5 MW
  - Peak Beam Power 125 MW
- MB-IOT is desired RF amplifier source in High β accelerator section (84 sockets)
- High efficiency for all power levels of operation
- Higher efficiency than klystrons operated in back-off
**MB-IOT Requirement & CPI-Thales Consortium Approach**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ESS specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>704.42 MHz</td>
</tr>
<tr>
<td>Peak power</td>
<td>&gt; 1.2 MW</td>
</tr>
<tr>
<td>RF pulse length</td>
<td>up to 4 ms</td>
</tr>
<tr>
<td>RF duty factor</td>
<td>up to 5%</td>
</tr>
<tr>
<td>Beam voltage</td>
<td>&lt; 50kV</td>
</tr>
<tr>
<td>Beam current</td>
<td>&lt; 45 A rms</td>
</tr>
<tr>
<td>Efficiency</td>
<td>&gt; 60%</td>
</tr>
<tr>
<td>Gain</td>
<td>&gt; 20 dB</td>
</tr>
<tr>
<td>Bandwidth (-1dB)</td>
<td>&gt; 2MHz</td>
</tr>
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<td>Tube life</td>
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- Multi-Beam solution for megawatt class output power at beam voltage < 50kV
- TED & CPI consortium approach to develop the MB-IOT solution
- Team collaboration during design phase
- Shared manufacturing & testing of first prototype
  - Electron guns, HV ceramic assemblies, input circuit, and HV enclosure built by TED
  - MB-IOT tube assembly, magnet system, and cart system built by CPI
  - Testing at CERN by TED
MB-IOT Design Features

- **Self-contained cart with MB-IOT and ancillary sub-systems**
  - 10x individual IOT guns situated on a bolt circle
    - Cathode Loading 3.6 A/cm², 90K predicted life
  - Single coaxial output cavity
  - 10x individual isolated collectors
  - Beams focused with single solenoid and optimized pole pieces for small transverse field
  - Coaxial window & coax to WR1150 WG transition

- **Input Circuit w/ HV Enclosure**
  - Single RF input 1-5/8” with custom RF splitter delivering balanced RF to 10x guns
  - Single 50 kV DC blocker
MBIOT Simulation Tools

RF Design
- HFSS

Beam Optics
- MICHELLE (NRL/Leidos)
- OPTIQUE

Solenoid Focusing System
- MagNet (Infolytica)
- MAXWELL

Beam-wave interaction
- MAGIC
- IOT Code (TED internal)

Thermal & Mechanical Analyses
- ANSYS

48 kV, 3.8 A rms, Qe = 100
Pout = 132 kW
Efficiency = 72%
MB-IOT Predicted performance

- Optimum Qex is 95 ~ 105
- Operating point @ 1.3MW:
  - Beam voltage 45 - 48 kV
  - Beam current 38 – 40 A rms
  - Efficiency > 70%
  - Grid to cathode bias -160V
  - Drive power 6-8 kW
- -1dB bandwidth is 4.5 MHz (2 MHz spec.)
MB-IOT Manufacturing

### Output Cavity Assembly

- No braze issue (all copper)
- No deformation (was challenging given the large diameter-to-height ratio)
- Center conductor of the output line (tapered section) is copper coated to prevent multipactor
MB-IOT Manufacturing

Output Cavity Cold Tests

- Successive machining to achieve target cavity frequency and Qex before final brazing.

- Cavity tuning diaphragm kept close to the neutral position, only changed after baking for final tuning.

- Mode found at 31.3 MHz above fundamental; HFSS prediction was 35 MHz above.

- Two modes are close to the 2nd harmonic and one below the 3rd harmonic: 1322 MHz (-87 MHz from 2F), 1599 MHz (+190 MHz from 2F), and 2028 MHz (-85 MHz from 3F); no issue expected.
**MB-IOT Manufacturing**

- **Gun Array Assembly**
  - Individual gun derived from Thales IOT TH795 (extended ceramic length)

- **Collector Array Assembly**
  - Individual isolated collectors derived from existing products

- **Existing CPI High power klystron RF window (air cooled)**
  - 1MW CW and to 3 MW in pulse mode

- **Gun & Collector arrays aligned and welded on cavity assy**

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MB-IOT Manufacturing

Exhaust

- Prototype re-exhausted after heater issues
  - Replaced 2x guns
  - Quick turnaround (~1 day) for each replacement
  - Tube successfully held vacuum after 3 exhaust cycles
- Cathodes processed with 2 heater power supplies
- Grids outgassing completed
- Hi-pot tests
  - anode to grid 65 kV
  - cathode to grid 1500 V

Tube on exhaust station

Setup for 25A heater process

Set up for hipotting grid to anode up to 65 kV

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Input Circuit Layout

- Single RF input
- Single stub tuner for adjusting overall match and grounding coax inner conductor
- DC Blocker design employed at CPI for HV service to 50 kV in existing single beam IOT’s
- Custom RF splitter (delivers balanced RF to 10x guns)
- 10x individual coax RF gun feeds with sliding short & sliding slug for frequency tuning and matching; phase tuning not required if properly tuned.
MB-IOT Manufacturing

- DC Blocker: Hi-pot tested at 60kV; good RF match (VSWR ~ 1.05) @ 704 MHz
- RF Splitter: Power equally balanced over the 10 outputs
- 10 x RF gun feeds fitted on the splitter assembly
**IPC Tuning Procedure**

- The single DC blocker / RF splitter architecture has some constraints
  - All RF gun feeds at HV (personal safety issue during tuner adjustments)
  - No way to tune and match individual RF gun feed from the splitter input

- The IPC has been designed such that each individual RF gun feed can be disconnected from the splitter and plugged to an external network analyser

- A method has been developed to tune the individual RF gun feeds without HV
  - KG spacing is loaded with a low current beam in diode mode
  - Set dynamic impedance \( \frac{dV_g}{dl_g} \) close to 25Ω (beam impedance at 1.2MW)
  - Circuit is tuned and matched at low level
  - Excellent match of \( S_{11} = -52 \) dB at 704 MHz
  - 8 MHz bandwidth @ -20 dB
MB-IOT Manufacturing

Mounting the Input Circuit & HV enclosure on the MB-IOT

- Alignment fixtures required to align IPC socket contacts with guns
- Final fine lowering with help of 4 screw jacks
Test Facilities at CERN

- Test stand developed by CERN in close collaboration with Thales

- HV power supply
  - Charger from OCEM
    - 50kV 160kW
  - Capacitor bank (80µF) from AVX
    - 2.5 kV drop during HV pulse (4ms)
  - Crowbar from CERN (LEP)

- HV deck
  - 10x individual heater supplies
  - 10x individual grid bias supplies plus 1x common bias supply; this scheme (patented) helps to align the grid transfer curves of all guns
  - Particular attention to HV cabling layout

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Test Facilities at CERN

Control command & interlocks

- Slow control with PLC
- Fast interlock during and outside the pulse
- Individual collector current
- Total collector current
- Total body current
- Individual heater and grid bias

10 kW RF driver

- 10 x 1kW SSPA from BTESA
- 10-to-1 planar cavity combiner from CERN
MB-IOT Testing at CERN

- **Prototype on test stand**
  - IPC mounted during installation
  - Hi-pot test to 53 kV @ 120µA (leakage)
  - Individual gun feeds tuned at low power in diode mode (no HV)
  - Individual collector currents aligned (adjusted grid voltage, no RF)
Scope Capture

- Rise time is 1ms, flat top is 1ms and fall time is 1.5ms needed for stable operation of the power supply.
RF at 1ms Pulse Length/3% Duty

- 1.2 MW output power achieved with 8.7 kW input power (21.4 dB gain)
- 38.2 A cathode current (37.3A collector and 870mA body current)
- 0.04 A idle current between pulses
- RF efficiency of 69.8 % (during pulse)
- Cathode to grid bias voltages ranged from -145V to -168 V with an average value of -158 V.
- Good input matching (RL= -21 dB)
- No oscillations or anomalies detected
- Efficiency at 600 KW output ~57% at 45 kV
- Achieved 62.7% for 600 kW at 38 kV
Collector currents dispersion

- Except for Gun #8 which presented some uncharacteristic behavior, the collector current dispersion was quite low at approximately 0.3 A at 1.2 MW.
- It should be noted that Gun #8 appeared a bit apart with the most negative cut-off voltage and a lower slope \(\frac{dl_{\text{beam}}}{dV_{\text{grid}}\text{.}}\)
Performances with 9 beams

- 1x RF gun feed removed and replaced with a 50Ω load
- Limited to 900 kW due to loss of one of the 10 driver modules
- No oscillation on higher order mode detected

- 9-Beam Performance in dashed curves
- 10-Beam performance in solid curves
RF at 4 ms Pulse Length / 5% Duty

- Performance was tracking data at 1 ms pulse length
- **!! Tube Fault occurred at 1 MW**
  - strong vacuum trip
  - then RF instabilities detected starting as low as 400 kW peak at 200 µsec RF pulse length
  - possible to re-condition at shorter pulse length, but never to 1.2 MW level
  - tube could be temporarily operated at 600 kW with 800 µs pulse duration
Performance at 600 kW

Phase Characteristics vs Output Power, Beam Voltage, and Grid Voltage

- Phase vs Output Power
- Phase vs Vg @ Po = 600 kW
- Phase vs Vg @ Po = 600 kW

Output Power Characteristics vs. Beam Voltage and Grid Voltage

- Output Power vs Beam Voltage
- Output Power vs Grid Voltage
Analysis and Repair

- Disassembly confirmed loss of contact on center conductor near the window was the root cause.
- Window design used on many pulse and CW UHF klystrons
- The window design has been modified with additional compliance to prevent disengagement
- The unit was been repaired, re-baked and is presently at CERN waiting final testing.
MB-IOT Performance Summary

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<td>Beam voltage</td>
<td>&lt; 50kV</td>
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</tr>
<tr>
<td>Efficiency (beam conversion)</td>
<td>&gt;65%*</td>
<td>69.8%**</td>
</tr>
<tr>
<td>Gain</td>
<td>&gt; 20 dB</td>
<td>21.4 dB</td>
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- Summary of initial results at 1 ms/14 Hz
  - ** 67.4% including 40mA idle current
- Solenoid Power 222W
  - 3.8A x 1.7V
  - 18A x 12V
- Filament Power 2750W
  - 11Vx25A x 10
- Idle Current Power 1750 W
  - 40 mA x 45kV x 0.97
Summary

- MB-IOT prototype manufactured and tested
  - Results proved design capability and meeting of ESS primary requirements
    - 1.2 MW peak
    - 69.8% Beam conversion efficiency at 1.2 MW
    - Achieved 63% at 600 kW
    - 21.4 dB of gain

- Next Step – MB-IOT arrived at CERN in Dec 2017. Full power testing and characterization to begin in September
Acknowledgement

- We would like to thank Morten Jensen and the ESS RF group for their support
- We also thank Eric Montesinos of CERN for testing support and recommendations

THANK YOU FOR ATTENTION