MATERIAL PLASMA EXPOSURE EXPERIMENT

PERFORMANCE SPECIFICATIONS OF 70/105 GHZ GYROTRON AND ASSOCIATED COMPONENTS

Prepared by

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831-6283

Managed by

UT-BATTELLE, LLC

For the

US DEPARTMENT OF ENERGY

under contract DE-AC05-00OR22725

Performance Specifications of 70/105 GHz Gyrotron and Associated Components for the Material Plasma Exposure Experiment (MPEX) Project

MPEX-03-SPC-001

Author:

Tim Bigelow — Digitally signed by Tim S. Bigelow Date: 2020.11.17 11:05:53 -05'00'

Tim Bigelow, ECH Technical Lead — Date

Reviewer:

LaTravia N Harmon — Digitally signed by LaTravia N Harmon Date: 2020.11.17 11:26:18 -05'00'

LaTravia Harmon, Quality Assurance Representative — Date

Approvers:

Digitally signed by Michael C. Kaufman Date: 2020.11.17 14:45:16 -05'00'

Michael Kaufman, CAM Plasma Source & Heating — Date

Arnold Lumsdaine — Digitally signed by Arnold Lumsdaine Date: 2020.11.17 15:00:04 -05'00'

Arnold Lumsdaine, MPEX Project Engineer — Date

Distribution:

Phillip Ferguson, MPEX Project Director

Performance Specifications of 70/105 GHz Gyrotron and Associated Components for the Material Plasma Exposure Experiment (MPEX) Project

MPEX-03-SPC-001

Revision History

Revision	Date	DESCRIPTION OF CHANGE	REVISION TYPE	
			Major	Minor
0	Nov 13, 2020	Initial Issue	☐	☐
			☐	☐
			☐	☐
			☐	☐

Performance Specifications of 70/105 GHz Gyrotron and Associated Components for the Material Plasma Exposure Experiment (MPEX) Project

MPEX-03-SPC-001

CONTENTS

1 SCOPE

This technical specification defines the requirements for the design, test, manufacture, and packaging for a gyrotron, gyrotron magnet, and matching optics unit. This technical specification includes requirements in terms of performance and provides criteria for verifying compliance with the requirements.

The gyrotron is a microwave oscillator that shall be designed to operate steady-state at 600 kW and at two frequencies: 70 GHz and 105 GHz. Unless specifically noted, all the following requirements and specifications shall be applicable to operation at either frequency.

The gyrotron Matching Optics Unit (MOU) is designed to efficiently couple the gyrotron output power from the diamond window into a corrugated waveguide with the required mode purity. This design must function reliably at both the 70 GHz and 105 GHz gyrotron operating frequencies with minimal beam pointing adjustment required to switch between frequencies.

The gyrotron magnet system shall be a cryogen-free cryocooler based superconducting magnet and supplied as a complete system including a helium compressor for the cryo-cooler, helium lines, magnet power supplies, and power supplies control system installed in a rack along with associated cabling.

2 APPLICABLE DOCUMENTS

[1] MOU-TL Interface Drawing, MPEX-03-DRWG-15-A100-B

3 TECHNICAL REQUIREMENTS

3.1 FUNCTIONAL AND PERFORMANCE

3.1.1 The gyrotron system shall output 70.0± 0.1 GHz.

3.1.2 The gyrotron system shall output 105.0± 0.1 GHz. A small offset is acceptable depending on F1/F2 mode index.

3.1.3 The gyrotron system shall have a Matching Optics Unit (MOU) and have a minimum output power of 600 kW at each operating frequency as measured at the output of the MOU. The tolerance range is +5% / -0% at both frequencies.

3.1.4 The operating power range shall be at < 50 kW to 600 kW.

3.1.5 The gyrotron and associated components shall be designed for steady state output operations.

3.1.6 The minimum pulse length shall be 1 μs.

3.1.7 The gyrotron system shall be designed to optimally couple its output power to the HE_{11} waveguide mode in 63.5 mm circular corrugated waveguide.

3.1.8 The HE_{11} mode purity shall be >96% at 1 m downstream of the MOU-TL interface in the corrugated waveguide at both the 70 GHz and 105 GHz operating frequencies.

3.1.9 The HE_{11} mode plane-polarization shall be >99% at 1 m downstream of the MOU-TL interface in the corrugated waveguide at both the 70 GHz and 105 GHz operating frequencies.

3.1.10 The DC to RF efficiency shall be >40% with depressed collector mode at 600 kW. A lower efficiency is acceptable at lower power.

3.1.11 The DC to RF efficiency shall be >30% with non-depressed collector mode at 600 kW. A lower efficiency is acceptable at lower power.

3.1.12 The system shall operate in an external vertical magnetic field of ≤ 20 G.

3.1.13 The system shall operate in an external horizontal magnetic field of ≤ 5 G.

3.1.14 The microwave leakage power shall be < 5 mW/cm^2 measured at < 1 m from the gyrotron and/or MOU.

3.1.15 The x-ray radiation shall be < 2.5 mR/hr. at the surface of the gyrotron or integrated shielding and with the MOU installed.

3.1.16 The DC hold-off voltage between the MOU and gyrotron output window assembly shall be >30 V. This assumes that the output window is at collector potential.

3.2 VACUUM

3.2.1 The gyrotron vacuum shall be maintained by two ≥20 L/s vac-ion pumps.

3.2.2 The high voltage connectors on the gyrotron vac-ion pumps shall have mechanical safety guards.

3.2.3 A vacuum pumping port shall be provided on the MOU.

3.2.4 The MOU pumping port shall include a microwave cutoff screen. The microwave leakage power at 105 GHz into the vacuum duct shall be < 10 dBm.

3.2.5 The MOU vacuum pumping port conductance shall be > 10 L/s measured with the cutoff screen in place.

3.2.6 The vacuum leak rate for the MOU shall be < 1E-8 std cc/s helium. This rate may be verified either with blank-off flanges or while connected as a system.

3.3 COOLING

3.3.1 The gyrotron collector, gyrotron body, and MOU coolant shall be demineralized water. The Seller shall specify the water chemistry requirements necessary to meet the performance and lifetime requirements.

3.3.2 The gyrotron and associated components shall operate with a combined maximum water flowrate of 950 L/min (250 gpm).

3.3.3 The gyrotron and associated components shall operate with a water supply temperature range of 18-30°C.

3.3.4 The gyrotron and associated components shall operate with a demineralized water coolant resistivity of at least 1 MΩ-cm.

3.3.5 The gyrotron collector shall operate with a maximum coolant pressure of 17.6 bar (240 psig). A lower pressure is preferred.

3.3.6 The gyrotron collector coolant pressure drop shall be < 14.8 bar (200 psig).

3.3.7 The gyrotron cathode high voltage insulation shall be FR-3 oil or equivalent.

3.3.8 The gyrotron cathode oil coolant flowrate shall be a maximum of 3.8 L/min (1 gpm).

3.3.9 The gyrotron output window shall have a dedicated cooling loop.

3.3.10 If the gyrotron output window coolant is demineralized water, then the diamond braze must be protected by coating. Alternate coolants are acceptable.

3.3.11 The MOU shall operate with a maximum coolant pressure of 7.9 bar (100 psig).

3.3.12 Standard swage fittings for the coolant connections are preferred.

3.4 GYROTRON

3.4.1 The maximum cathode voltage shall be -85 kV.

3.4.2 The gyrotron must withstand at least 10 J (in < 10 μs) stored energy in a cathode arc discharge.

3.4.3 The maximum beam current shall be 25 A.

3.4.4 The maximum body voltage shall be 40 kV when operated in depressed collector mode.

3.4.5 The maximum body current shall be 100 mA.

3.4.6 The gyrotron shall utilize a diode-type gun, unless an alternate type is approved by the Company.

3.4.7 The maximum cathode heater voltage shall be 26 V at DC or 60 Hz.

3.4.8 The maximum cathode heater current shall be 20 A at DC or 60 Hz.

3.4.9 The cathode heater lifetime should be > 10,000 hours and be designed to generate minimum magnetic field at the cathode.

3.4.10 The collector lifetime shall be > 16,000 hours and shall be verified by fatigue analysis.

3.4.11 The collector shall be rated for at least 1.5 MW power dissipation at steady state operating conditions.

3.4.12 The gyrotron output window shall be single-disk CVD diamond that is edge-cooled.

3.4.13 The gyrotron output window loss tangent shall be < 5E-5.

3.4.14 The maximum temperature on the gyrotron outer surface shall be < 45°C.

3.4.15 The maximum height of the gyrotron shall be 3 m.

3.4.16 The maximum weight of the gyrotron shall be 2000 kg.

3.5 MATCHING OPTICS UNIT

3.5.1 The MOU shall be designed to interface with 63.5 mm corrugated waveguide at the MOU output port. The interface to the waveguide via an MOU-TL adapter flange is given by [1].

3.5.2 A microwave pickup port at the focusing mirror shall be provided and couple into a WR15 waveguide. The broad side axis of the waveguide shall be aligned perpendicular to the polarization of the microwave beam.

3.5.3 Two optical arc detector pickup ports shall be provided. These ports shall be cutoff below 105.1 GHz and be sealed to vacuum. They shall be angled to look toward the center of the gyrotron output window and arranged on opposite sides of the output beam.

3.5.4 The MOU shall possess built-in water-cooled absorbing structures to absorb any stray microwave radiation outside the main beam.

3.5.5 At least two internal stray-power monitors shall be provided. These may be calorimetric monitors.

3.5.6 The direction of the MOU output beam shall be vertically upwards.

3.5.7 The location of the MOU output beam axis shall be < 1 m from the MOU input port.

3.5.8 The MOU mirror[s] shall maintain the specified mode purity and beam coupling efficiency during steady state operations with normal coolant flow. Mode purity and coupling efficiency shall not be degraded by vibrations, thermal expansion, vacuum cycling, or gyrotron power cycling.

3.5.9 The maximum temperature on the MOU outer surface shall be < 45°C.

3.5.10 The maximum temperature on the MOU output flange connection shall be < 40°C.

3.5.11 The MOU shall fit within a volume of 1.2 m × 1.2 m × 1.2 m.

3.5.12 The maximum weight of the MOU shall be 1000 kg.

3.6 MAGNET

3.6.1 The magnet shall be superconducting.

3.6.2 The magnet shall be cryogen-free cryocooler-based.

3.6.3 The magnet shall be supplied as a complete system including helium compressor for the cryo-cooler, helium lines, magnet power supplies, and power supplies control system installed in a rack along with associated cabling.

3.6.4 The magnet shall possess beam steering coils for steering in the X and Y horizontal planes.

3.6.5 The magnet current stability shall be ± 0.1 mA.

3.6.6 The nominal current shall completely stabilize (to ±1% around the operating point) upon adjustment in < 2 minutes.

3.6.7 The magnet control system supply voltage 120 or 208-240 VAC at 60 Hz allowing for a voltage tolerance of ± 10%. Three-phase power is allowed. Systems that can operate at both 50 Hz and 60 Hz are allowed.

3.6.8 The magnet coldhead compressor voltage shall be 208 or 480 VAC 3-phase at 60 Hz allowing for a voltage tolerance of ± 10%.

3.6.9 The magnet coldhead compressor current shall be < 40 A for 208 VAC or < 20 A for 480 VAC.

3.6.10 Cable lengths between magnet supplies/controls and the magnet shall be > 33 m and shall be designed for minimal voltage drop and adequate current capability.

3.6.11 The magnet shall cool down from room temperature to operating temperature in < 72 hours.

3.6.12 The magnet shall recover from a quench in < 24 hours.

3.6.13 The coldhead pressurized helium piping length shall be > 20 m.

3.6.14 The coldhead pressurized helium piping shall be equipped with Aeroquip-sealed fittings for pressurization and helium purity.

3.6.15 The magnet shall mount to gyrotron socket via a bolt circle. The interface specifications (bolt pattern, diameter, etc.) shall be provided by the supplier.

3.7 INSTRUMENTATION AND CONTROLS

3.7.1 Local magnet current programming shall be by digital keypad input or dial setpoint.

3.7.2 The magnet control and monitoring system shall be remotely-controllable and shall possess one or more of the following interface methods: Ethernet, RS-232, or RS-485.

3.7.3 Remote control and monitoring of the magnets must mimic local control.

3.7.4 The magnet temperature shall be monitorable between 2 and 300 K to ±10% with at least two separate sensors.

3.7.5 Magnet currents shall be monitored to ±0.001 A with a data acquisition response time of < 0.1 s.

3.7.6 Magnet voltages shall be monitored to ±0.001 V with a data acquisition response time of < 0.1 s.

3.7.7 The magnet system shall possess an external interlock tied to the current setpoints of each coil. This interlock shall be both via hardwired relay contacts and via remote interface.

3.7.8 The magnet system shall possess an internal startup interlock. The power supplies shall not be permitted to energize if any interlock is not satisfied. At minimum these interlocks are: coil temperatures, cold head compressor not operational.

3.7.9 The magnet system startup interlock shall be readable from local control panel and through remote interface.

3.7.10 The magnet system shall possess an internal ramp down interlock. The power supplies shall ramp down safely at maximum voltage if any interlock is not satisfied. At minimum, these interlocks are: coil temperatures, cold head compressor not operational, current excessively high.

3.7.11 The magnet system ramp down interlock shall be readable from local control panel and through remote interface.

4 STANDARDS

4.1 STANDARDS FOR WELDING AND BRAZING

4.1.1 All welds shall be qualified and produced in accordance with ASME Section IX, AWS, (or equivalent), or the applicable design and construction code.

4.1.2 Welding and brazing processes shall be conducted using qualified welding or brazing procedure specifications and qualified welders or brazers supported by a welder or brazer qualification test records. Welds shall be performed using non-magnetic materials. Each welding and brazing procedure specification shall be supported by a procedure qualification record.

4.2 STANDARDS FOR PRESSURE EQUIPMENT AND PIPING

4.2.1 Any piping used in the gyrotron, matching optics unit, and magnet shall comply with the ASME B31.3 piping codes.

5 TEST AND ACCEPTANCE REQUIREMENTS

Results of acceptance tests and inspections described in Section 5 shall be documented and supplied to the Company.

5.1 FACTORY ACCEPTANCE TESTS

The Factory Acceptance Test Plan shall include all testing necessary for factory acceptance of the gyrotron prior to shipment. All tests shall be performed at both operating frequencies, where applicable.

The Factory Acceptance Test plan shall include tests, measurements and inspections necessary to demonstrate that all of the requirements in Section 3 of this document are met. Additionally, the FAT plan will show how the following criteria and systems will be verified:

- Magnet system operation
- Gyrotron standoff voltage
- Gyrotron vacuum pressure (outgassing rate) with heater energization
- Gyrotron cooling water circuit integrity
- Matching Optics Unit cooling water circuits integrity
- Matching Optics Unit vacuum leak test
- High power pulsed operation
- RF power control over full range
- HE_{11} mode purity in waveguide
- High power steady-state operation

- Microwave leakage
- X-ray emission

The parameters to be achieved are given in Table 1. All tests shall be performed under Supplier-written test procedure.

Table 1. Acceptance Tests and Criteria

Parameter	Performance and Inspection/Verification
Diamond Window Measurement and Inspection	Prior to assembly, perform dimensional inspection (thickness, flatness) and loss tangent and reflection measurements.
Coolant Leak Test	None detectable at full static pressure for 1 hour.
Hipot	Cathode to body to -90 kV for 10 minutes. Body to ground to +40 kV for 10 minutes. No indications on vac-ion supply during test.
Coolant Flow Test	Full flow rate and pressure drop in all cooling circuits for 10 minutes
Filament & Cathode	Perform at least 10 full power cycles to ensure thermal and vacuum integrity of the cathode system
Minimum Power	600 kW for 1000 s into corrugated waveguide and calorimetrically instrumented dummy load with < 1% reflection in HE_{11} mode.
Minimum Pulse length	Four 1 hour test runs at >10% duty cycle at supplier location then one 8 hour test. Both frequencies for all tests into corrugated waveguide.
Minimum Efficiency	35% DC to RF conversion efficiency at 600 kW
Parameter Sensitivity	A set of test data shall be generated for output power variation with beam voltage, beam current, magnetic field slope, gun magnetic field, body voltage; 10 data points per graph with full output power shown on the graphs.
Minimum Mode Purity	95% coupled to HE_{11} waveguide Less than 5% stray and higher-order waveguide modes. Testing and analysis should be performed using IR camera and witness plates in 4 locations in the output beam for both the gyrotron and MOU output with >1 meter waveguide.
Window Power Handling	Output window temperature distribution should be monitored (without MOU is acceptable) during operation at several power levels and full power to ensure the cooling is adequate and window material is uniform
X-Ray Survey	X-ray measurement at 600 kW, at surface of gyrotron. < 2.5 mR/hr

5.2 SITE ACCEPTANCE TESTS

A complete Site Acceptance Test plan shall be supplied by the seller for review during the final design review which will encompass the testing to be performed for site acceptance of the gyrotron after installation at the Company's facility. All tests shall be performed at both operating frequencies, where applicable.

The Site Acceptance Test plan shall include all tests, measurements and inspections necessary to verify the gyrotron and associated components meet the requirements of this document after installation at the MPEX facility.

5.3 TESTS AND INSPECTIONS

5.3.1 All tests, measurements and inspections shall be performed using approved procedures.

5.3.2 Testing and inspection procedures shall comply with applicable design and construction codes.

5.3.3 All vacuum sealing welds, brazes and other joints shall be subject to helium leak testing.

5.3.4 Leak testing shall be performed after pressure or hydrostatic testing.

5.3.5 Pressure tests on coolant circuits shall be performed after fabrication is completed, primarily to verify the leak tight integrity but also to identify gross deformations or anomalies that may indicate design errors, material deficiencies, or defects in joining. The test pressure shall be established or based on the most applicable code of construction, appropriate test medium, and allowable stress. The maximum stress during pressure testing shall not exceed 90% of the minimum yield stress of the material. Acceptance leak tests on all vacuum components shall be performed after a minimum of three thermal cycles from ambient to the maximum possible operating temperature prior to leak testing.

5.3.6 The leak test shall be repeated after any repair or rework.

6 QUALITY ASSURANCE REQUIREMENTS

6.1 UNITS

6.1.1 All inspection and test data shall be reported in SI units.

6.1.2 Diagrams and/or drawings shall be presented in dual units, where the imperial unit of length shall be inches.

6.2 CALIBRATIONS

6.2.1 Measurement and test equipment shall be calibrated, and calibrations shall be current.

6.3 SOFTWARE

6.3.1 Any analysis software used in the design of the gyrotron shall be verified and validated for accuracy and correctness.

6.4 MATERIAL RECORDS

6.4.1 Material certification records shall be submitted for review and approval by the Company for all materials used in construction of the gyrotron and associated components.

6.4.2 Material certifications shall be compliant to EN 10204 (or equivalent).

7 PACKAGING, HANDLING AND SHIPPING

7.1 PACKAGING

7.1.1 The equipment shall be packaged, handled, and shipped to prevent mechanical or physical damage to it during transit.

7.1.2 Components shall be packed with adequate protection from thermal or mechanical stresses that may adversely affect the operation of the component.

7.1.3 All vacuum components shall be shipped dry (defined as <100 ppm water at ambient pressure and temperature), both internally and externally.

7.1.4 Volumes that have been pumped for helium leak testing shall be backfilled with dry nitrogen or dry air (<100 ppm H_2O) at a positive pressure of 0.1 MPa gauge and sealed or valved off, except where component is shipped under vacuum.

7.2 TRANSPORTABILITY

7.2.1 The equipment shall be packaged in a manner that facilitates movement, loading, and unloading by fork truck or crane. Any lifting fixtures or related hardware required to move, load, unload or install the equipment shall be considered part of the equipment.

7.2.2 Tilt and/or rough handling monitoring devices shall be required for shipment.

7.3 NAMEPLATE AND PRODUCT MARKING

7.3.1 The equipment shall be permanently marked to include the following information:

- Manufacturer
- Model number
- Serial number

7.4 STORAGE

7.4.1 Equipment shall be protected from damage during storage. Provisions shall be identified and implemented to ensure that the equipment is thoroughly drained and dried of all water prior to transport to prevent damage due to freezing.