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

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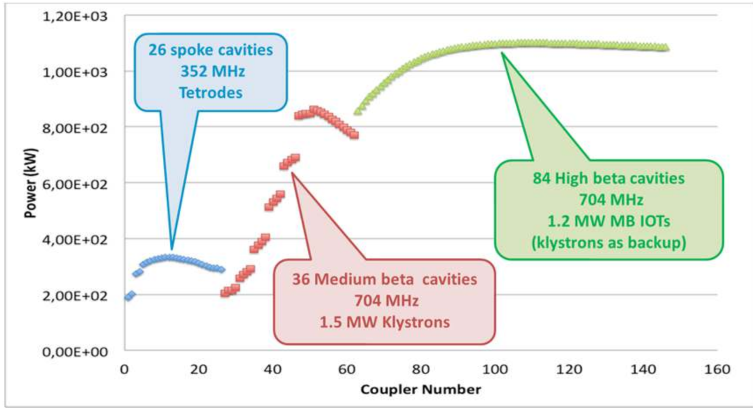
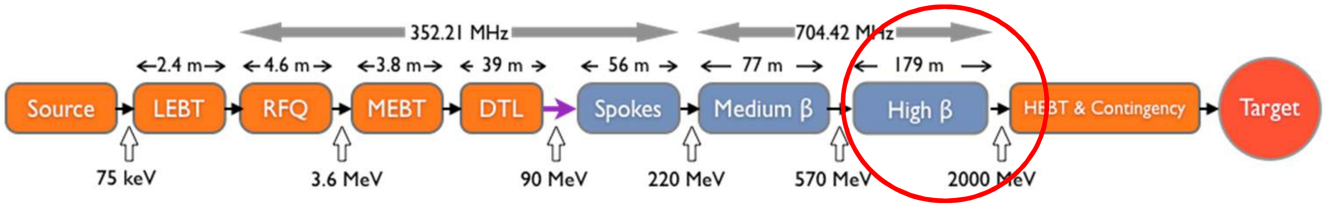
MB-IOT for European Spallation Source ESS

- **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

Parameter	ESS specification
Frequency	704.42 MHz
Peak power	> 1.2 MW
RF pulse length	up to 4 ms
RF duty factor	up to 5%
Beam voltage	< 50kV
Beam current	< 45 A rms
Efficiency	> 60%
Gain	> 20 dB
Bandwidth (-1dB)	> 2MHz
Tube life	> 50 kHrs

- 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

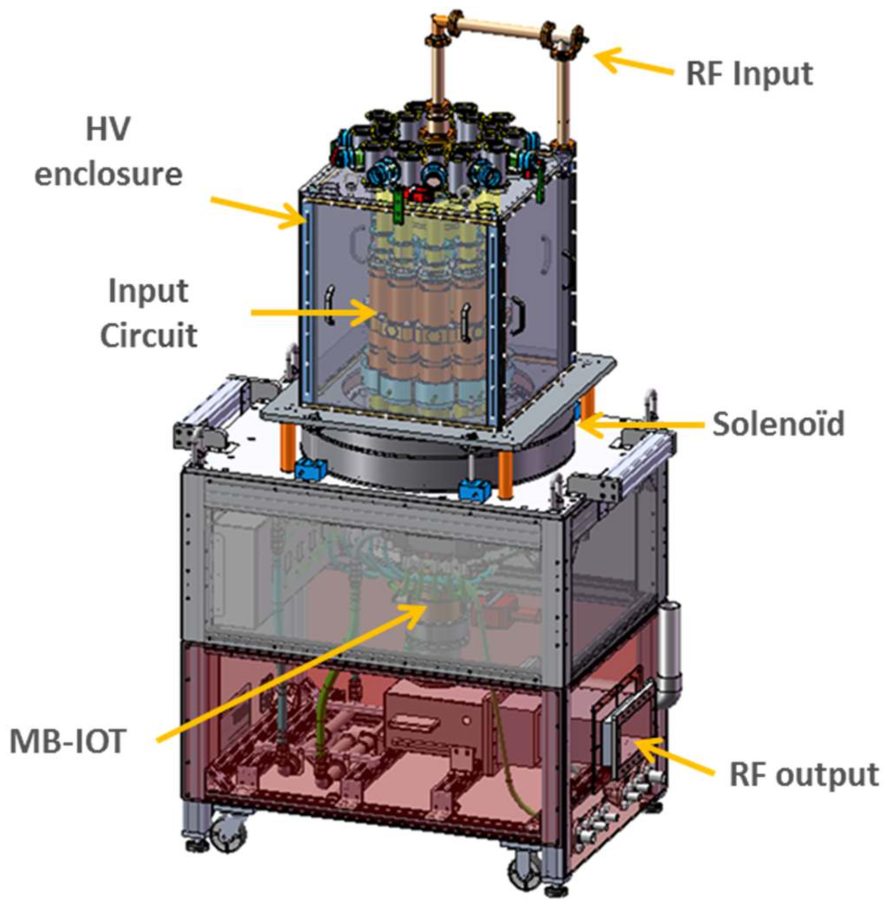
MB-IOT Design Features

Self-contained cart with MB-IOT and ancillary sub-systems

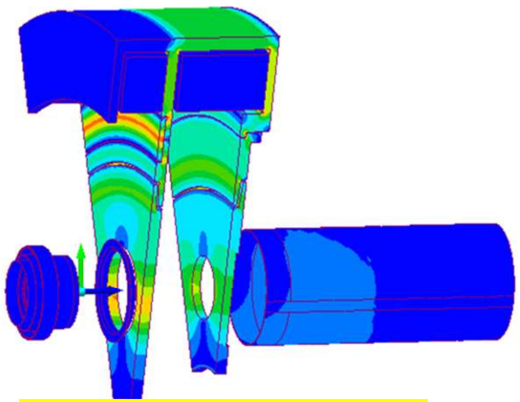
- 10x individual IOT guns situated on a bolt circle
  - Cathode Loading 3.6 A/cm2, 90K predicted life
- Single coaxial output cavity
- 10x individual isolated collectors
- Beams focused with single solenoid and optimized pole pieces for small transverse field
- Coaxial window & coax to WR1150 WG transition

Input Circuit w/ HV Enclosure

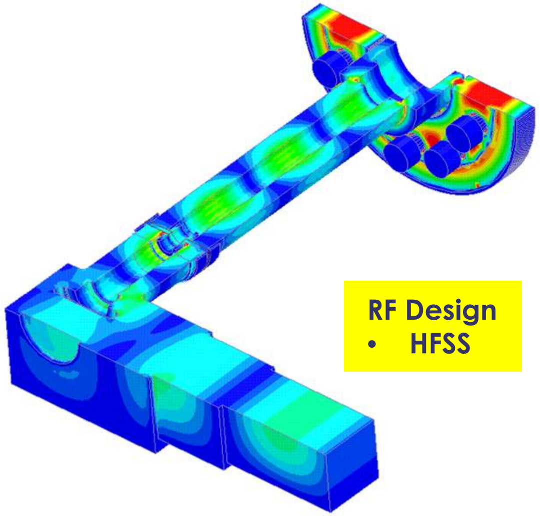
- Single RF input 1-5/8” with custom RF splitter delivering balanced RF to 10x guns
- Single 50 kV DC blocker



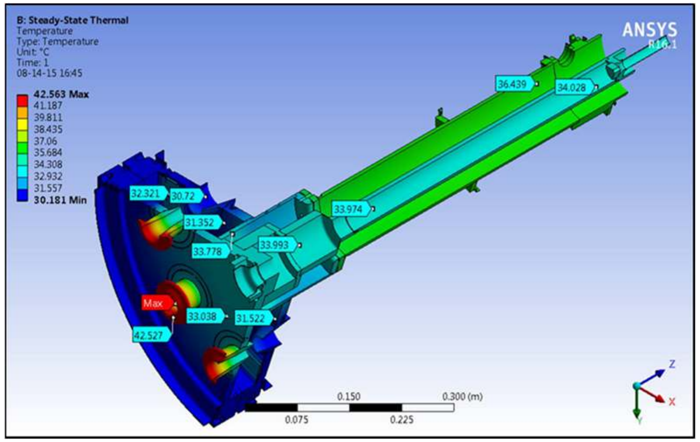
MBIOT Simulation Tools



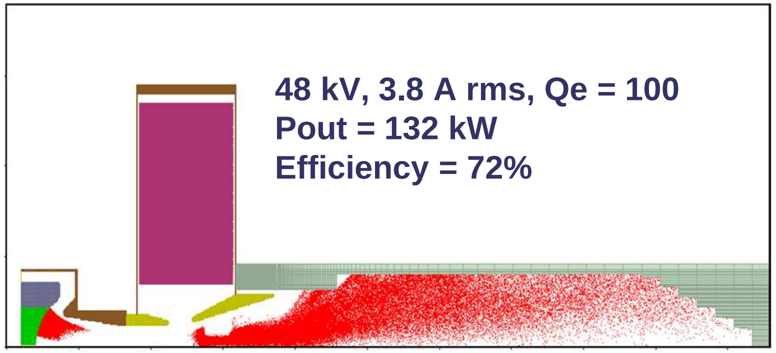
Solenoid Focusing System
- **MagNet (Infolytica)**
- **MAXWELL**



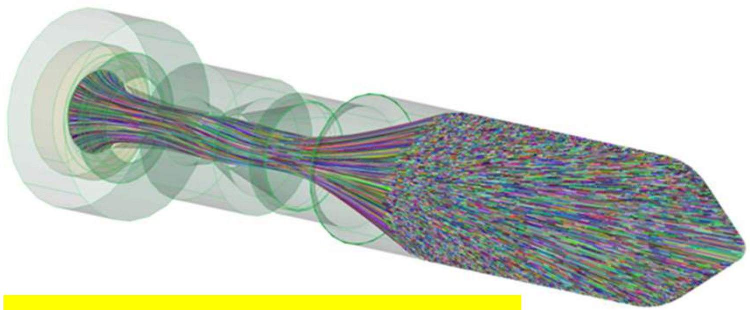
RF Design
- **HFSS**



Thermal & Mechanical Analyses
- **ANSYS**



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



Beam Optics
- **MICHELLE (NRL/Leidos)**
- **OPTIQUE**

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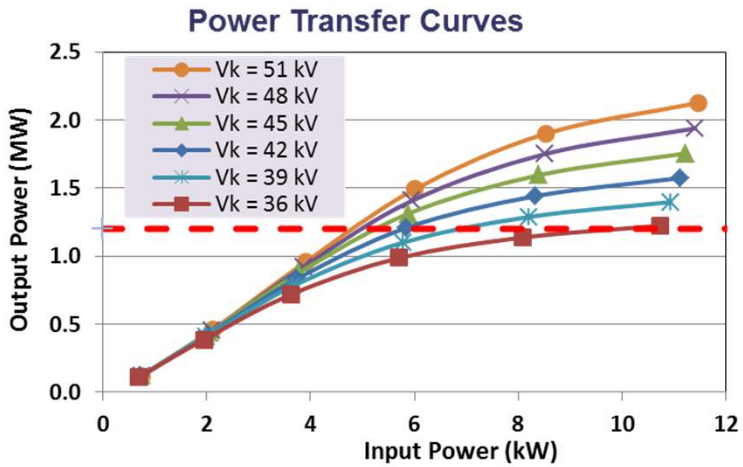
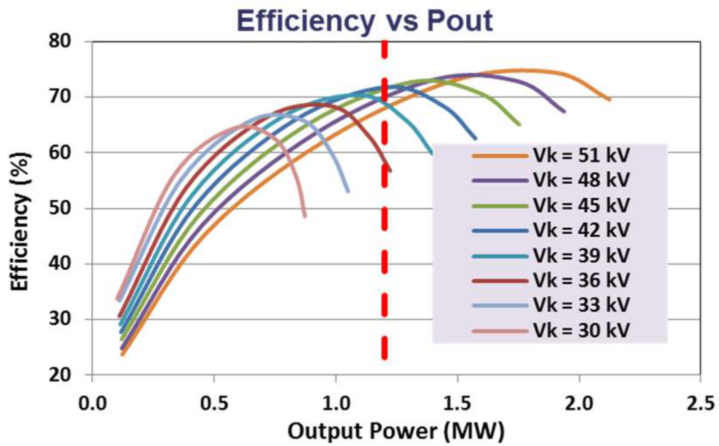
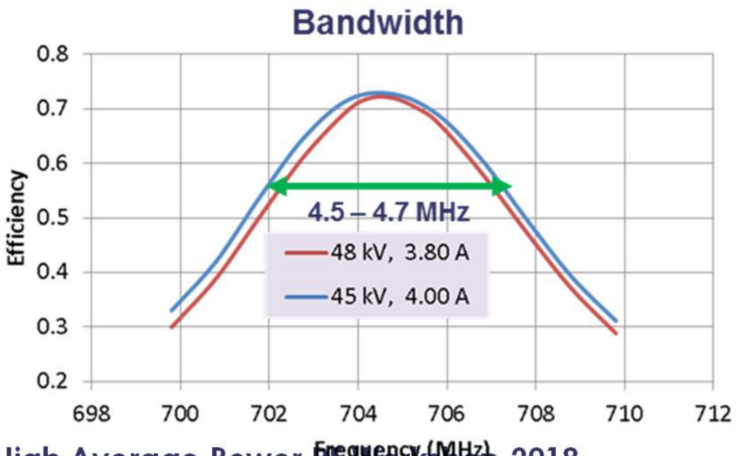
MB-IOT Predicted performance

- 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.)



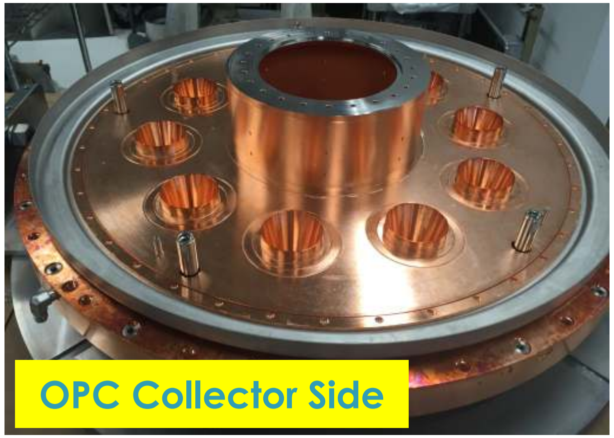


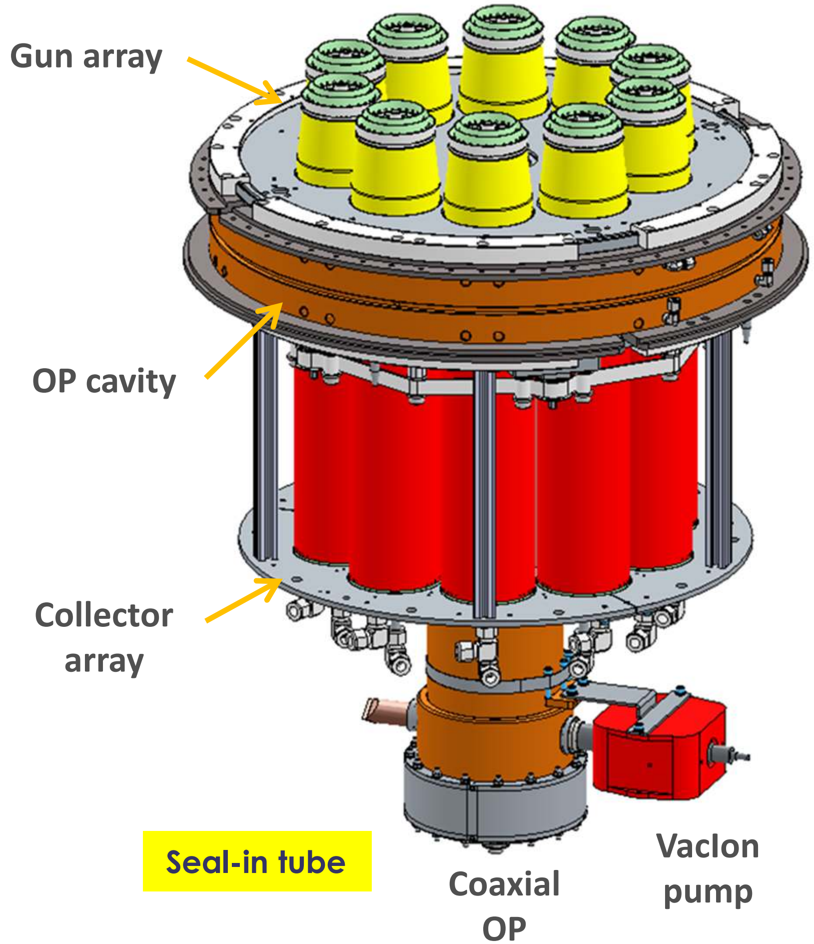


MB-IOT Manufacturing

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





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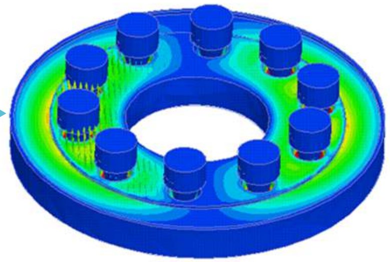
MB-IOT Manufacturing

Output Cavity Cold Tests

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

Cold test of MB-IOT output cavity

MB-IOT Manufacturing

Gun Array Assembly

- Individual gun derived from Thales IOT TH795 (extended ceramic length)

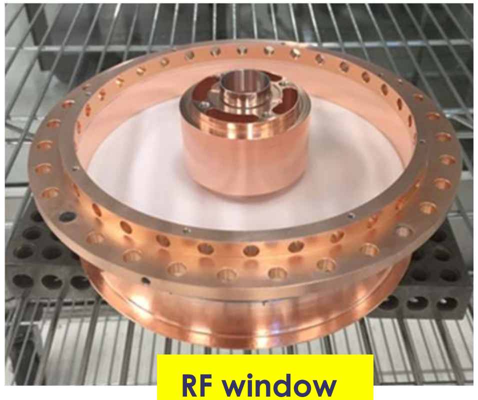
Collector Array Assembly

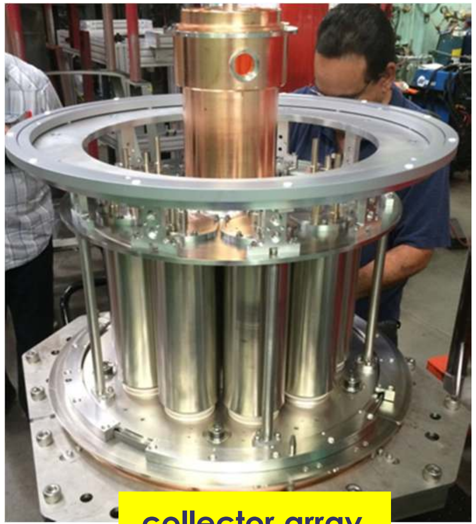
- Individual isolated collectors derived from existing products

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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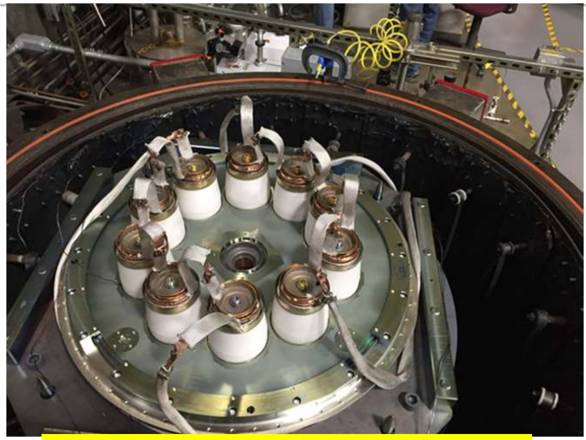
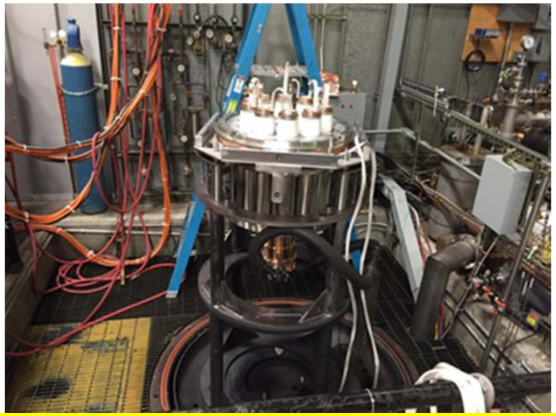
MB-IOT Manufacturing

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



Setup for 25A heater process



Tube on exhaust station

Set up for hipotting grid to anode up to 65 kV

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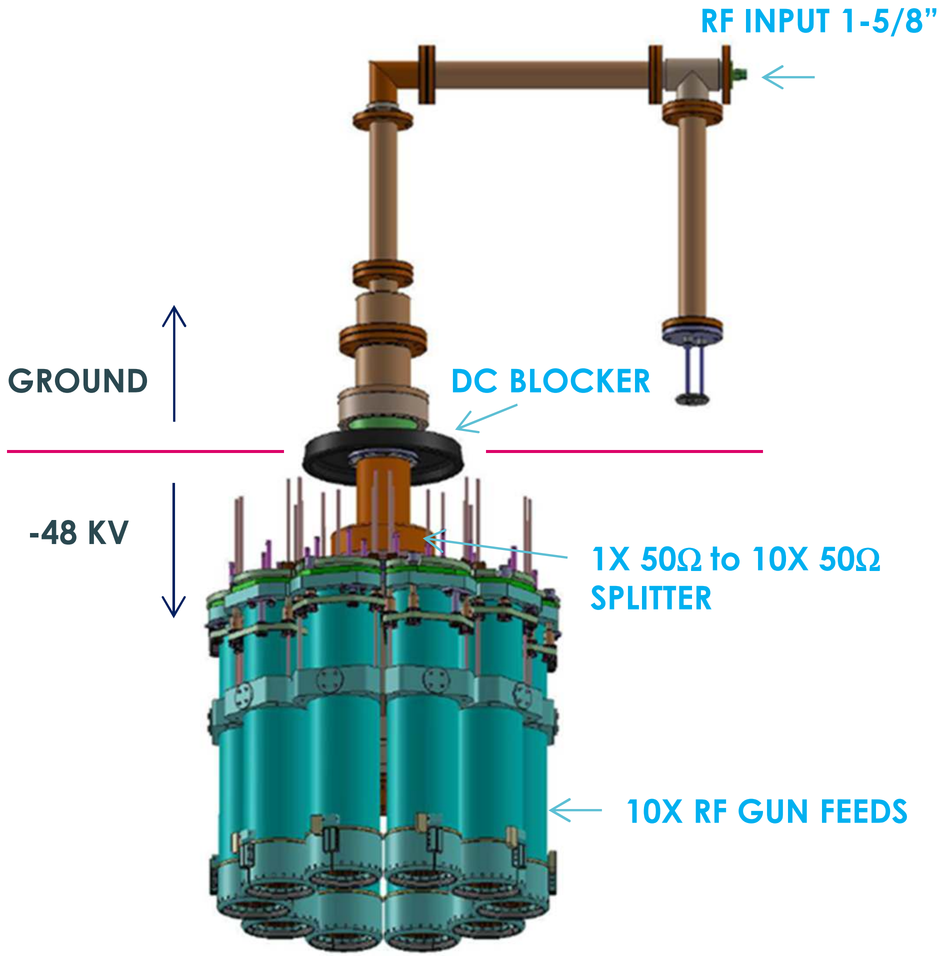
MB-IOT Manufacturing

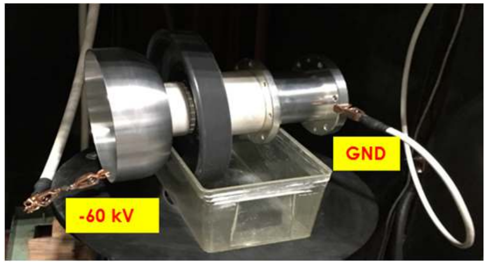
Input Circuit Layout

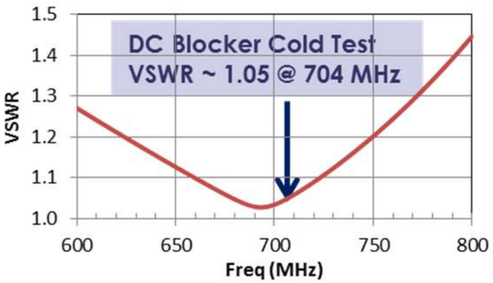
- Single RF input
- Single stub tuner for adjusting overall match and grounding coax inner conductor
- DC Blocker design employed at CPI for HV service to 50 kV in existing single beam IOT's
- Custom RF splitter (delivers balanced RF to 10x guns)
- 10x individual coax RF gun feeds with sliding short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

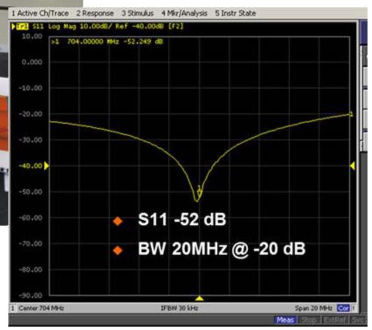


MB-IOT Manufacturing

- 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







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IPC Tuning Procedure

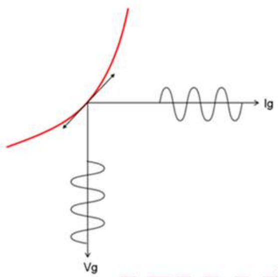
The single DC blocker / RF splitter architecture has some constraints

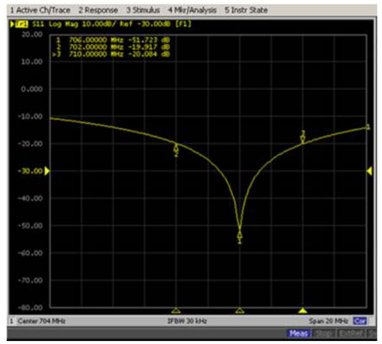
- All RF gun feeds at HV (personal safety issue during tuner adjustments)
- No way to tune and match individual RF gun feed from the splitter input

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 dV_g/dI_g close to 25Ω (beam impedance at 1.2MW)
- Circuit is tuned and matched at low level
- Excellent match of S11 = -52 dB at 704 MHz
- 8 MHz bandwidth @ -20 dB





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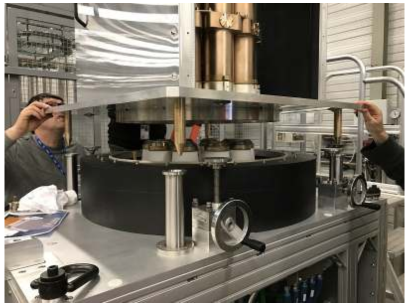
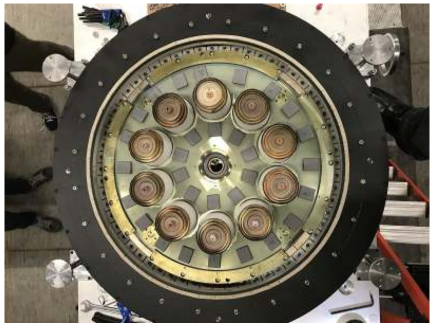
MB-IOT Manufacturing

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

- Alignement 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

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

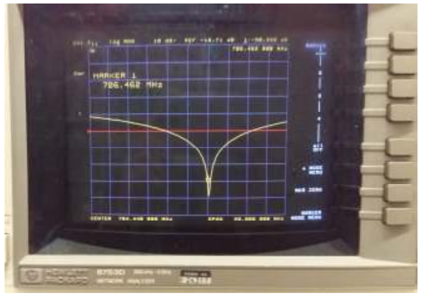
- 10 x 1kW SSPA from BTESA
- 10-to-1 planar cavity combiner from CERN

cavity combiner

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)



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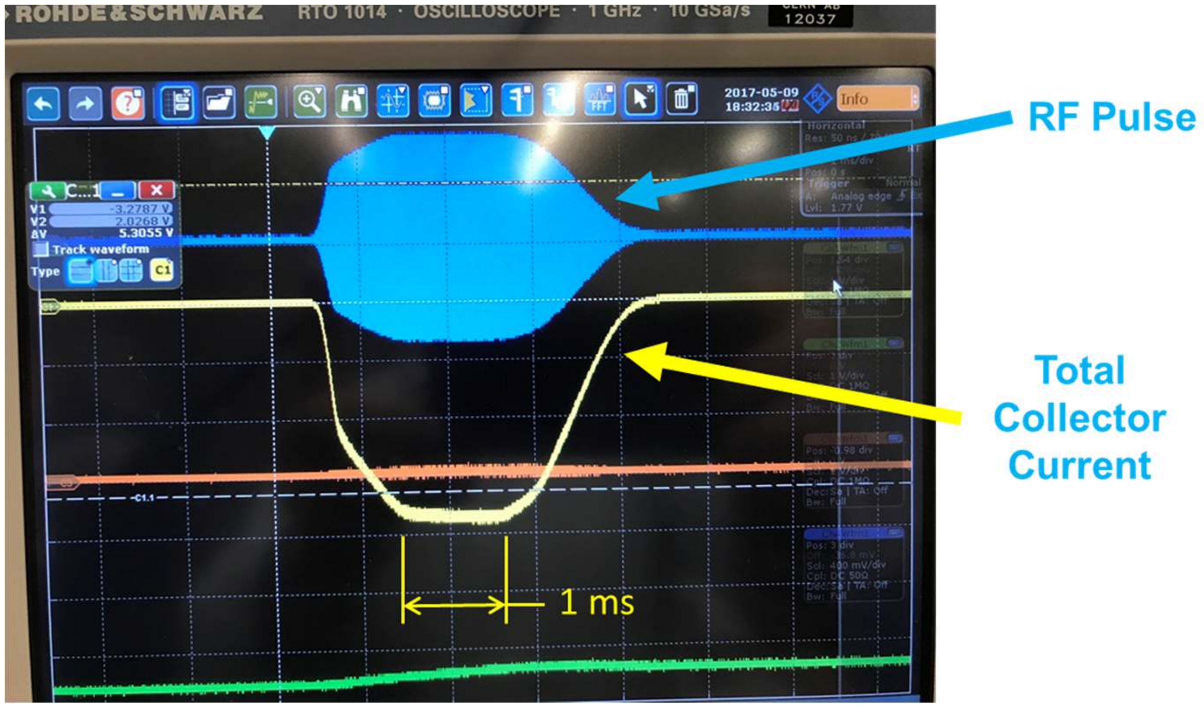
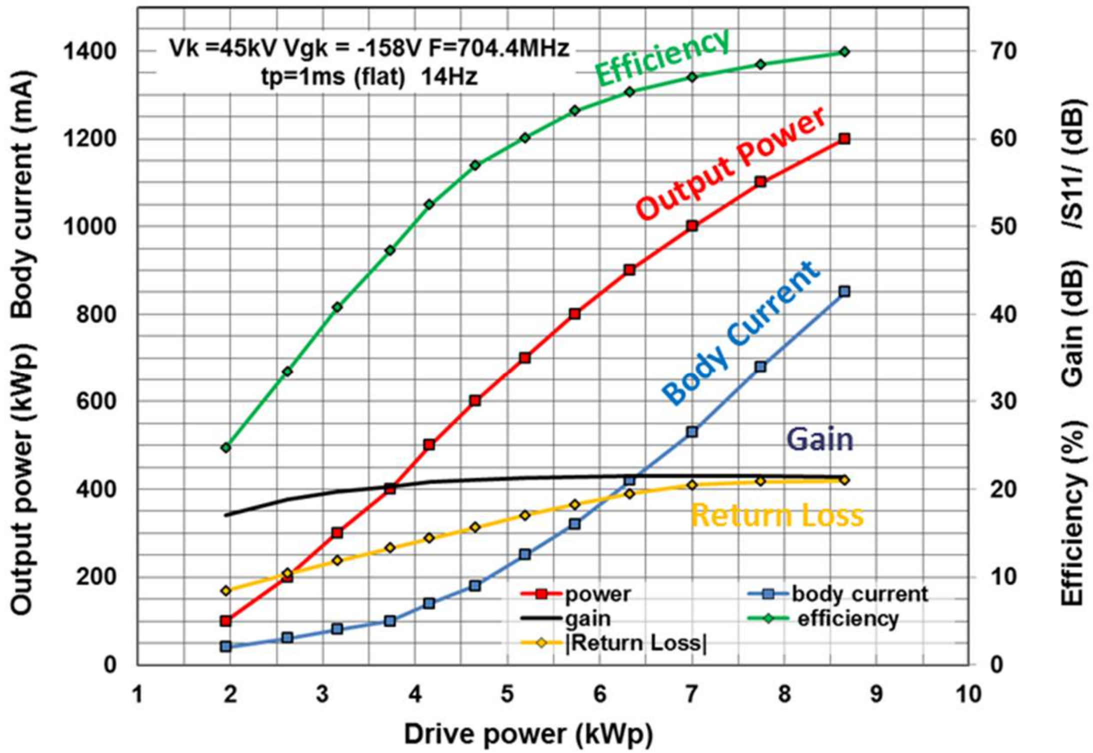
Scope Capture



- 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



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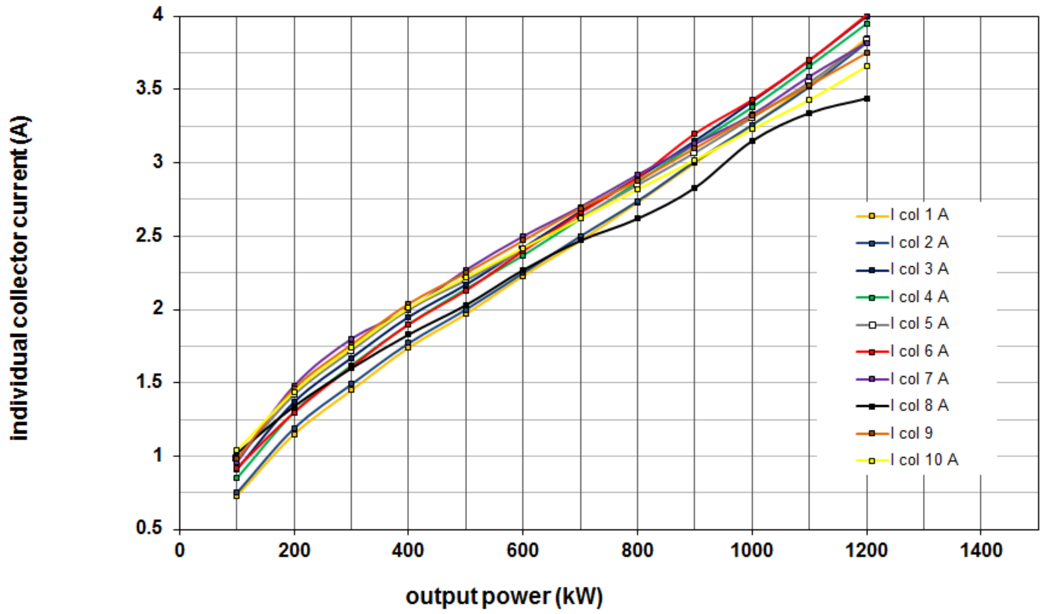
Collector currents dispersion

- 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 dIbeam/dVgrid.



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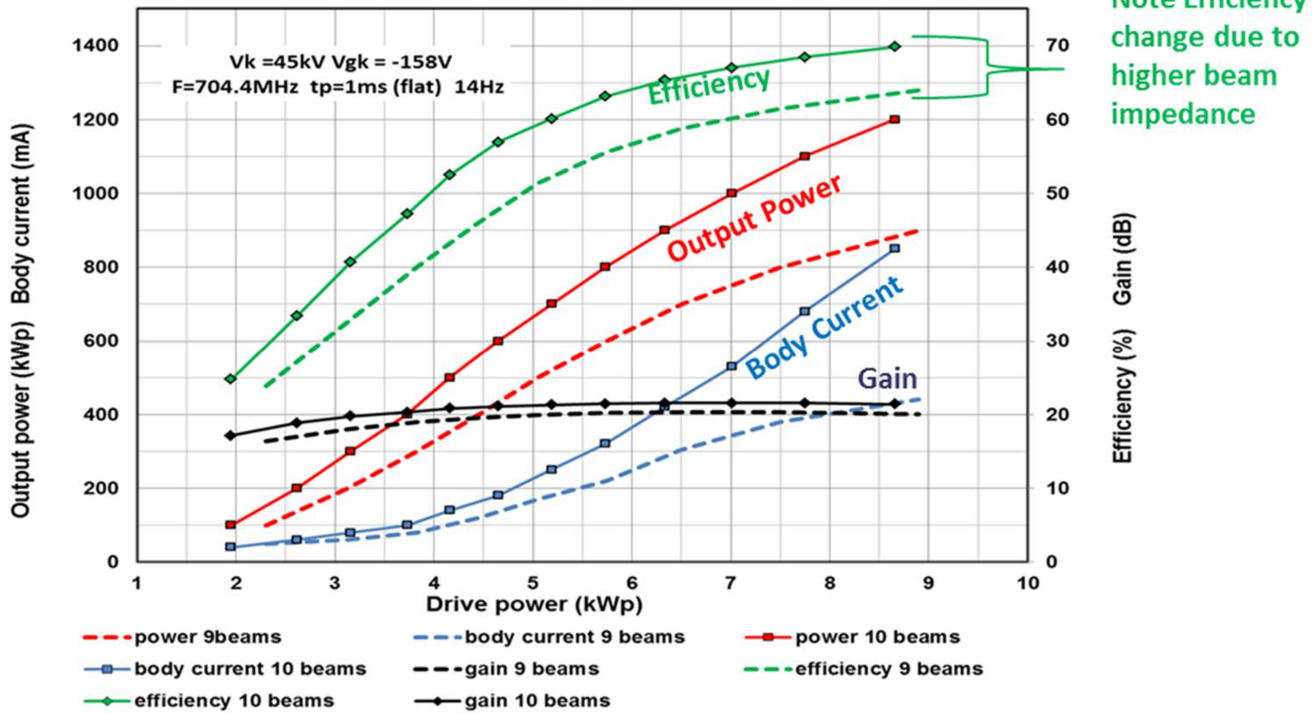
Performances with 9 beams

- 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

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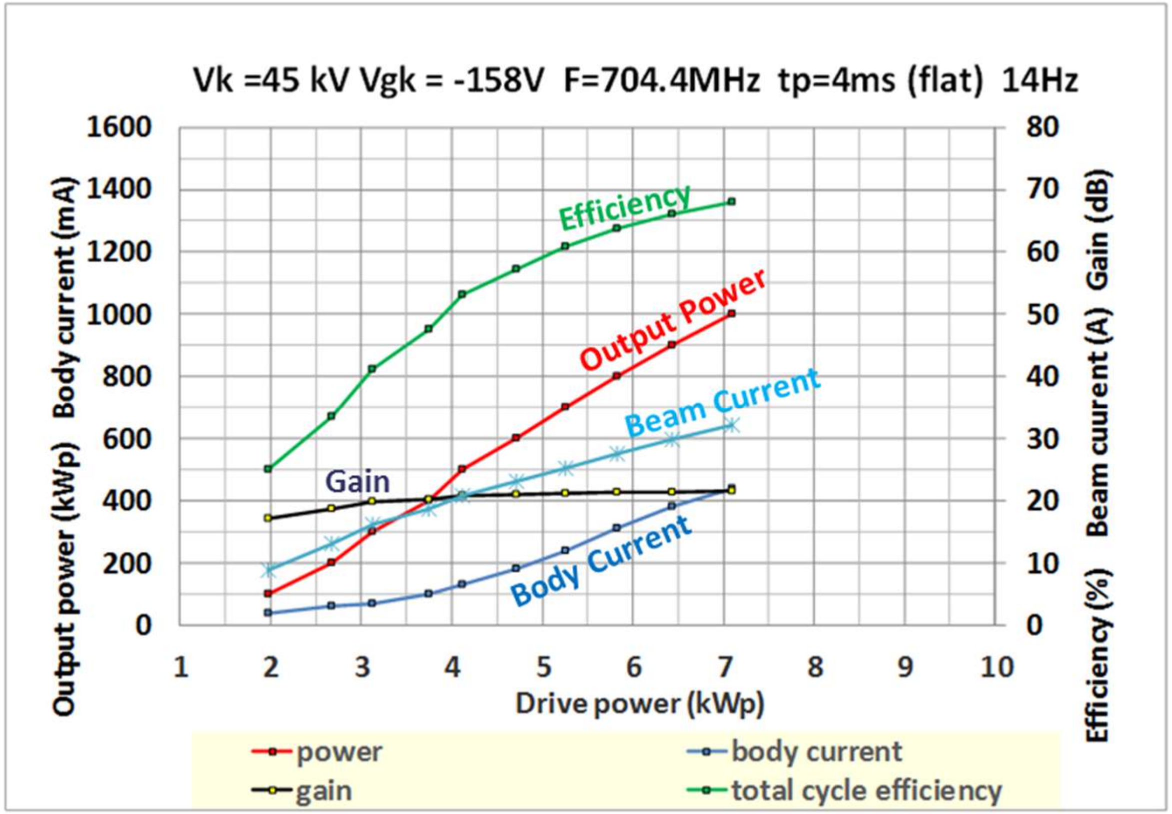
RF at 4 ms Pulse Length / 5% Duty

Performance was tracking data at 1 ms pulse length

!! Tube Fault occured at 1MW

- 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



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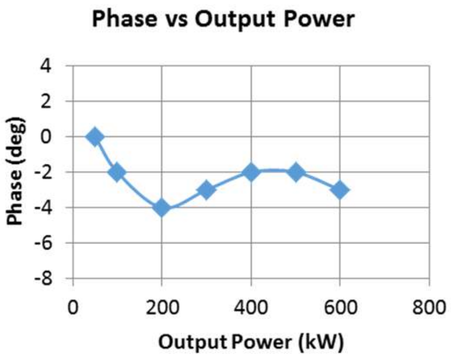
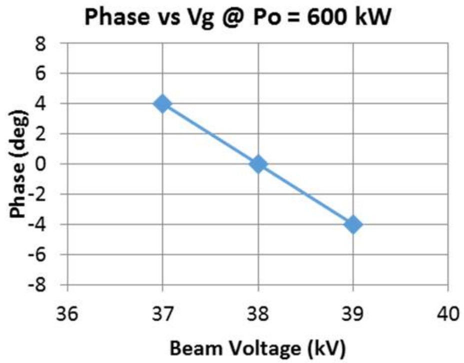
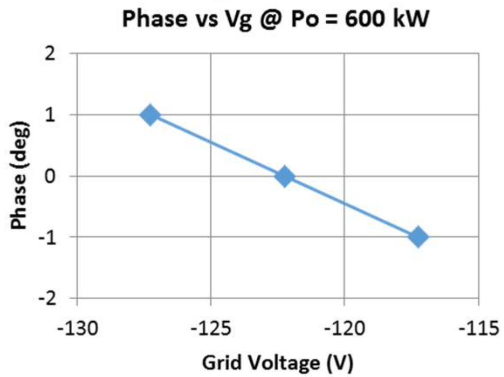
Performance at 600 kW

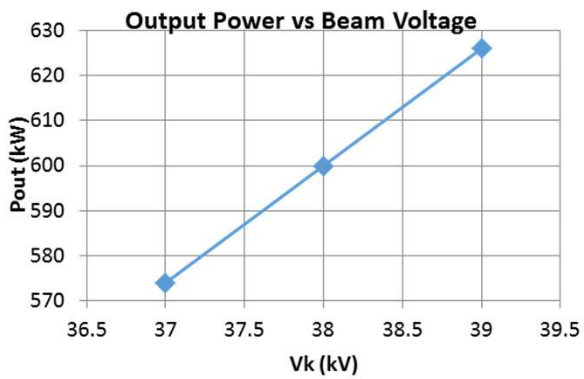
Phase Characteristics vs Output Power, Beam Voltage, and Grid Voltage

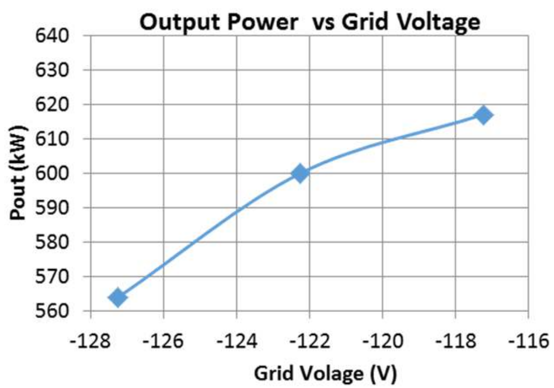






Output Power Characteristics vs. Beam Voltage and Grid Voltage





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

Parameter	ESS Specification	Preliminary Results
Frequency	704.42 MHz	704.42 MHz
Peak power	0.6 to >1.2 MW	Up to 1.2 MW
RF pulse length	up to 4 ms	1 ms to date
RF duty factor	up to 5%	3% to date
Beam voltage	< 50kV	45 kV
Beam current	< 45 A rms	38.2 A
Efficiency (beam conversion)	>65%*	**69.8%****
Gain	> 20 dB	**21.4 dB**
Bandwidth (-1dB)	> 2MHz	TBD
Tube life	> 50 kHrs	TBD

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

- 11Vx25Ax10

Idle Current Power 1750 W

- 40 mA x 45kV x 0.97

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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