Initial Factory Test of the L-3 L6200 Multi-Beam IOT for European Spallation Source

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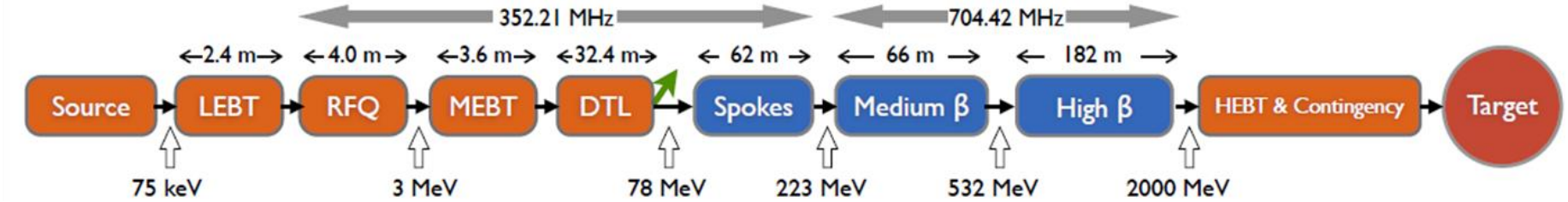
L-3 L6200 Multi-Beam IOT for ESS
Overview

- Introduction to the European Spallation Source (ESS)
- Advantages of IOTs for accelerator applications
- L-3 single beam accelerator IOTs
- L6200 multi-beam IOT (MBIOT)
  - Design overview and highlights
  - Fabrication
  - Test facility / power supply
  - Factory test results
- Conclusion

MBIOT for ESS
European Spallation Source (ESS)

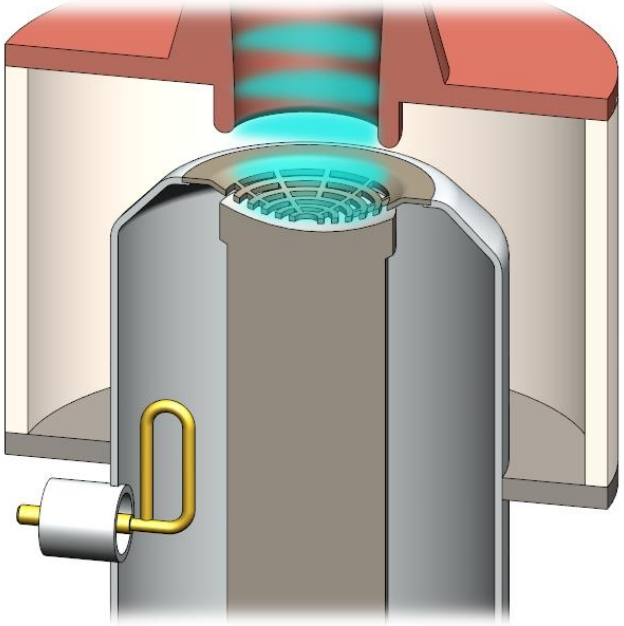
- The European Spallation Source (ESS) in Lund, Sweden will use a 2 GeV/62.5 mA proton linac to produce neutrons with higher energy and flux than any existing accelerator based facility
- Majority of RF power is used in the 704 MHz portion of the accelerator
  - To stay on schedule, ESS will use 36 klystrons to satisfy the 31 MW peak/ 1.2 MW average power medium beta requirement
  - High beta goes online after 2020; using 84 higher efficiency Super Power IOTs (SPIOTs) to generate the 92 MW peak/3.7 MW average power for this section enables ESS to meet ambitious energy conservation goals

Credit: ESS

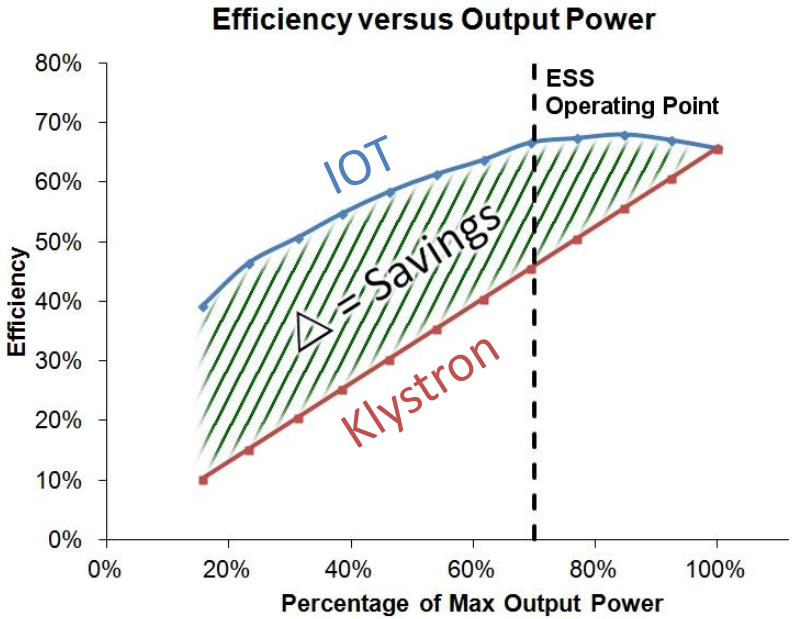


L-3 L6200 Multi-Beam IOT for ESS
The IOT Advantage

IOT beam power is proportional to RF drive, enabling high efficiency operation over a broad output power range, unlike a klystron where beam power is fixed



RF drive applied to the IOT grid, modulating the beam directly at the cathode



Test data from L4444 IOT compared to a klystron with the same efficiency at saturation

With RF output power backed off for fast amplitude and phase control, IOT efficiency is ~45% higher than that of a klystron

L-3 L6200 Multi-Beam IOT for ESS Specification and Design Goals

Parameter	Spec
Frequency	704.4 MHz
Peak Power	≥ 1.2 MW
Duty Cycle	4 % for ESS
Pulse Width	≤ 4 ms
Efficiency*	≥ 60 %
Gain	≥ 20 dB
Cathode Voltage	≤ 50 kV
Tube Life	≥ 50 khrs

*includes all associated power required to operate the tube

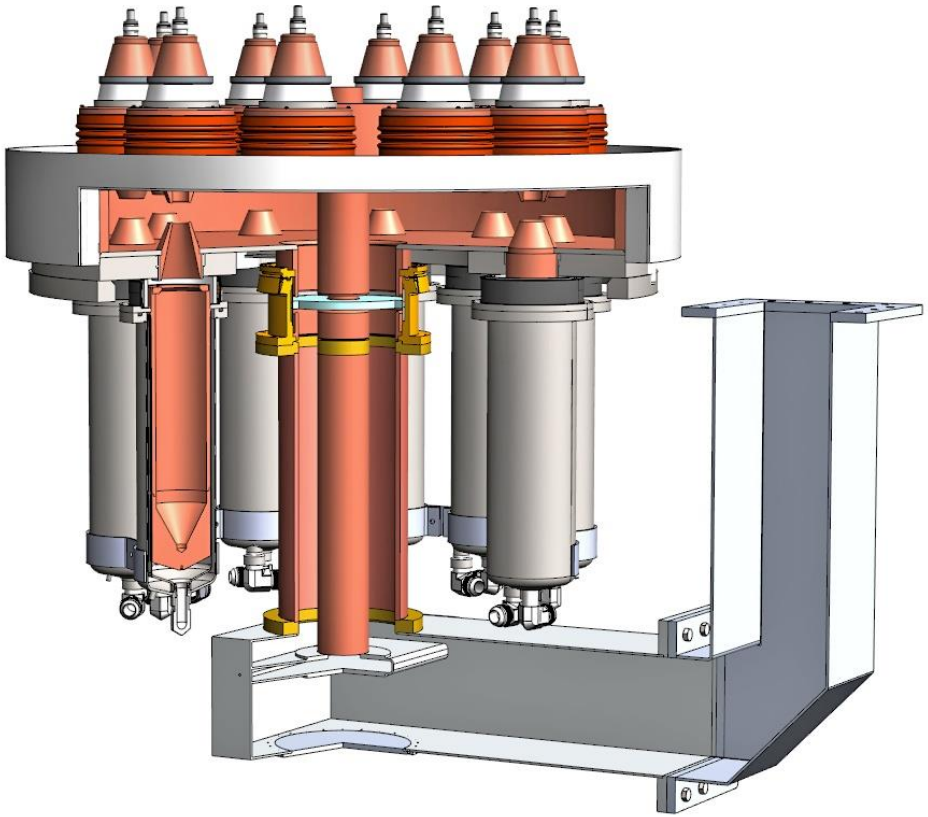
- Single beam UHF IOTs built for accelerator use typically produce on the order of 100 kW
  - The 90 kW CW L4444 used at BNL generates 130 kW of peak power in long pulse operation
- A megawatt class IOT operating at ≤ 50 kV mandates a multi-beam approach
  - The perveance of the individual beams must be kept low to meet gain and efficiency goals
- To ensure reliable operation, critical design parameters should be maintained near values that have been proven through years of field service

L-3 L6200 Multi-Beam IOT for ESS
Single Beam Accelerator IOTs

- Brookhaven NSLS-II Booster
  - 500 MHz, 90 kW CW
  - E_k 38 kV, I_k 3.5 A
  - Gain 22 dB, Eff 68%
- Brookhaven SRF Booster
  - 704 MHz, 65 kW CW
  - E_k 36 kV, I_k 2.7 A
  - Gain 22 dB, Eff 66%
- ALBA Synchrotron Light Source
  - 500 MHz, 80 kW CW
  - E_k 36 kV, I_k 3.2 A
  - Gain 23 dB, Eff 69%

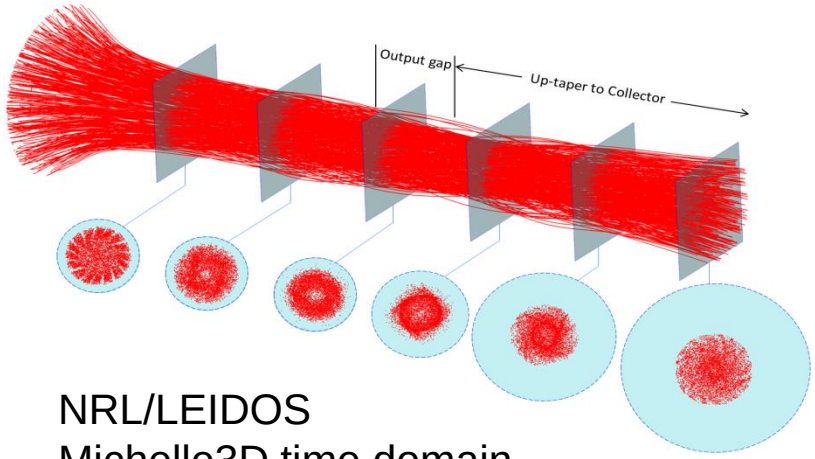
L-3 L6200 Multi-Beam IOT for ESS
Multi-Beam IOT Design Overview

- Ten electron guns
- Toroidal cavity design
- Each beam is focused using permanent magnets, eliminating the need for a solenoid power supply
- Designed with margin, for reliability and to support high duty applications
  - Coaxial window and T-bar coupler derived from SLAC 1.2 MW CW B-factory klystron design
  - Individual water cooled collectors rated for 35 kW DC
  - Full RF performance possible with less than 10 beams



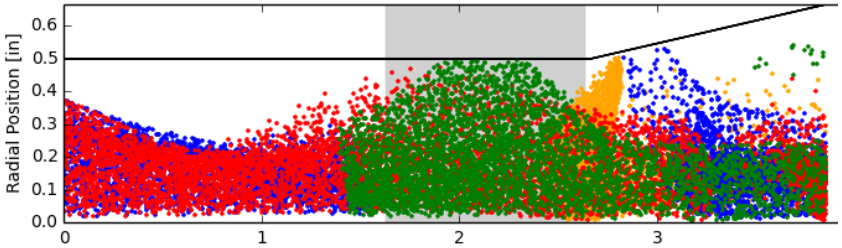
L-3 L6200 Multi-Beam IOT for ESS
Multi-Beam IOT Simulation Tools

Beam Optics

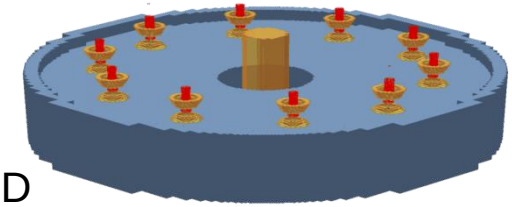


NRL/LEIDOS
Michelle3D time domain

Large Signal Analysis

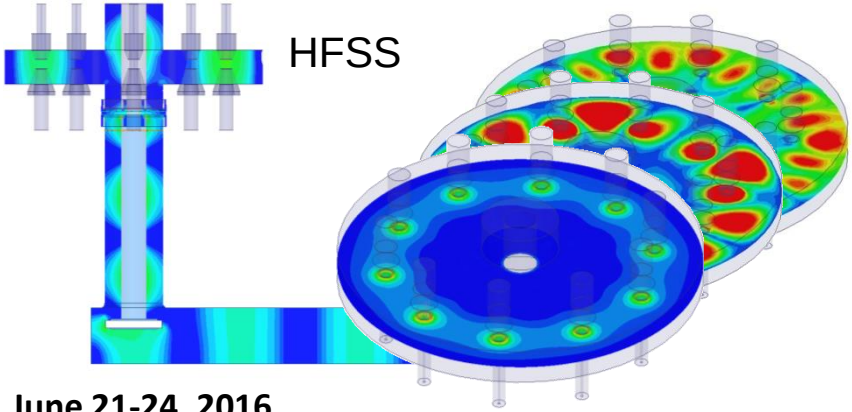


NRL/LEIDOS
TESLA for 2D
ATK MAGIC for 3D



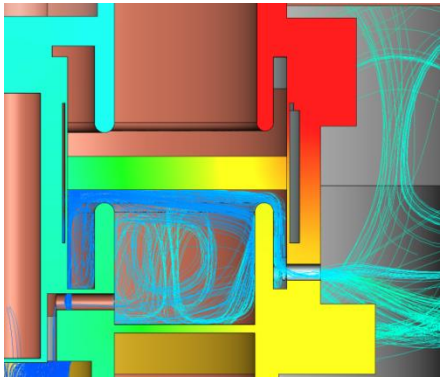
Cavity and Output Network RF

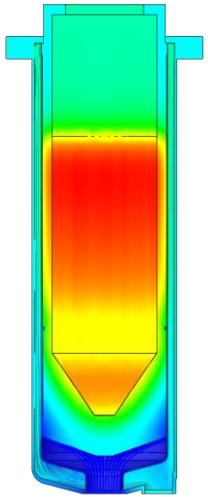
HFSS



Thermal Studies

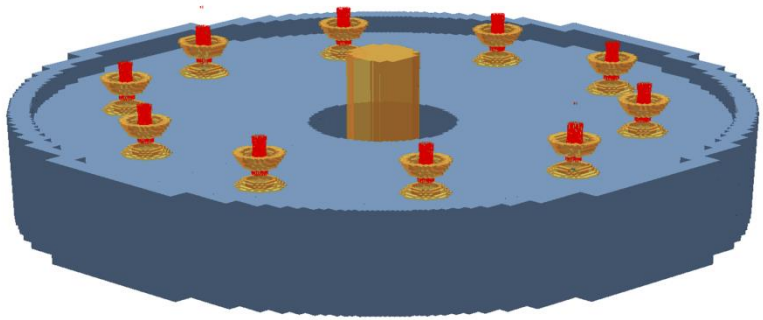
SolidWorks FloWorks



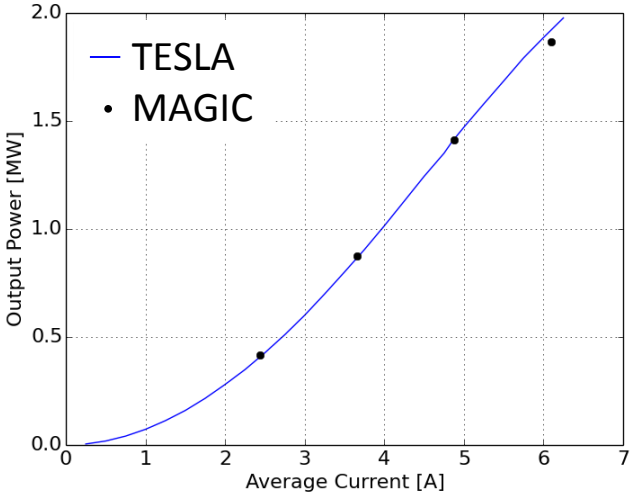


L-3 L6200 Multi-Beam IOT for ESS
Predicted RF Performance: Output Cavity Simulation

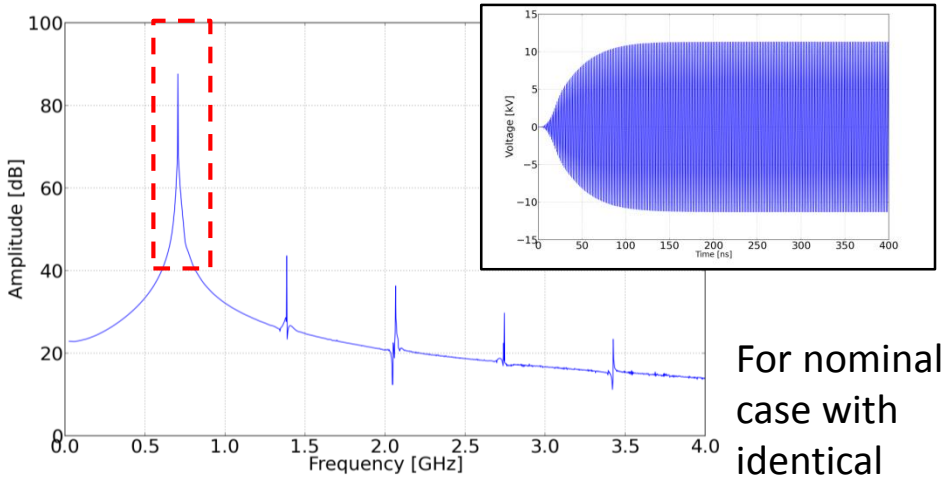
MAGIC3D PIC code is used to analyze non-uniformities (phase variation beam-to-beam, reduced number of beams), stability, and spurious emissions

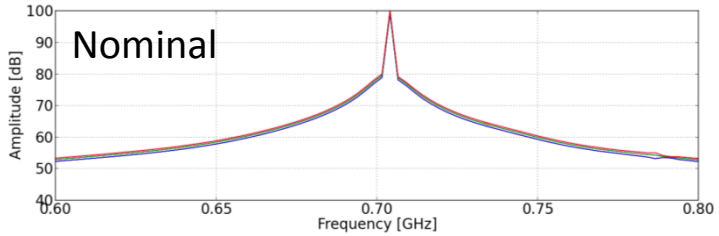


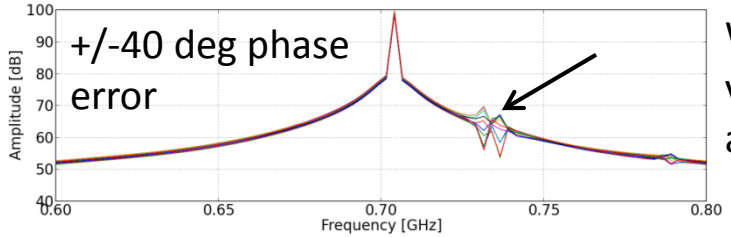
MAGIC Model with cavity top removed



Good agreement between codes



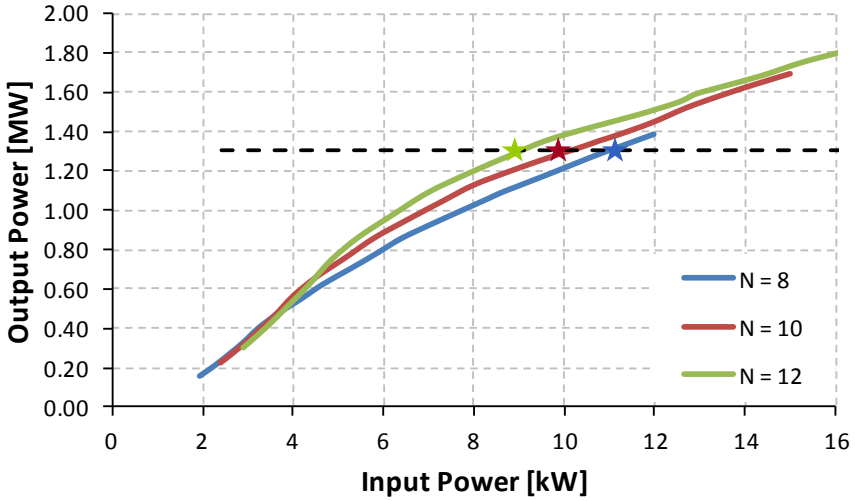


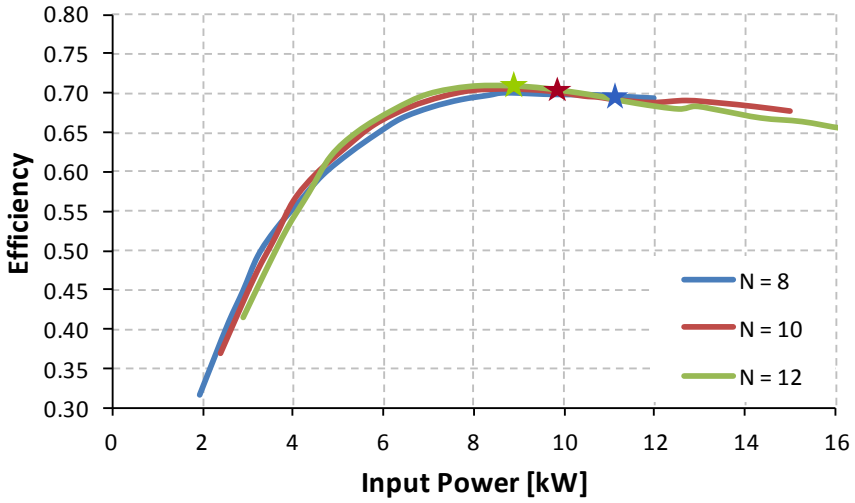


For nominal case with identical beams, a clean output spectrum is predicted

When phase varies, HOMs are excited

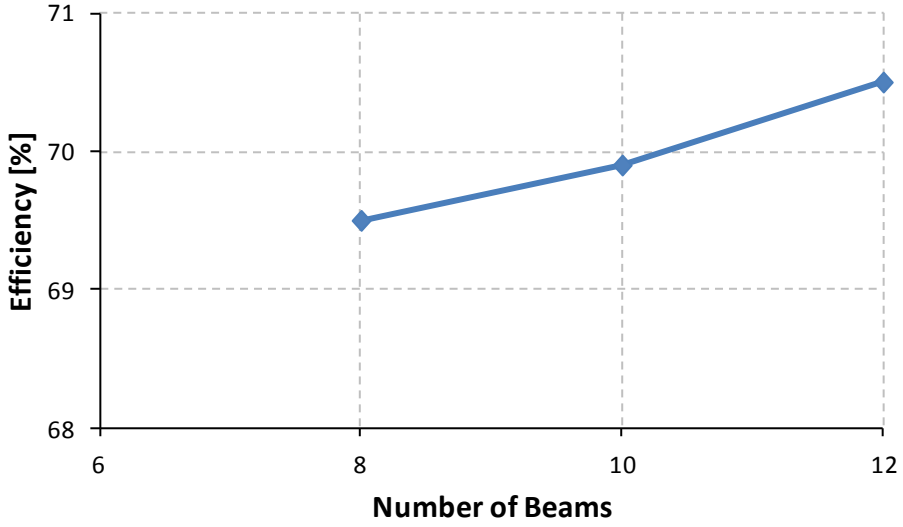
L-3 L6200 Multi-Beam IOT for ESS
Predicted RF Performance: Effect of Number of Beams





More beams increases efficiency and gain

- Ten beams chosen to balance performance with size and cost
- Simulations for 1.3 MW RF output power with beam voltage at 40 kV

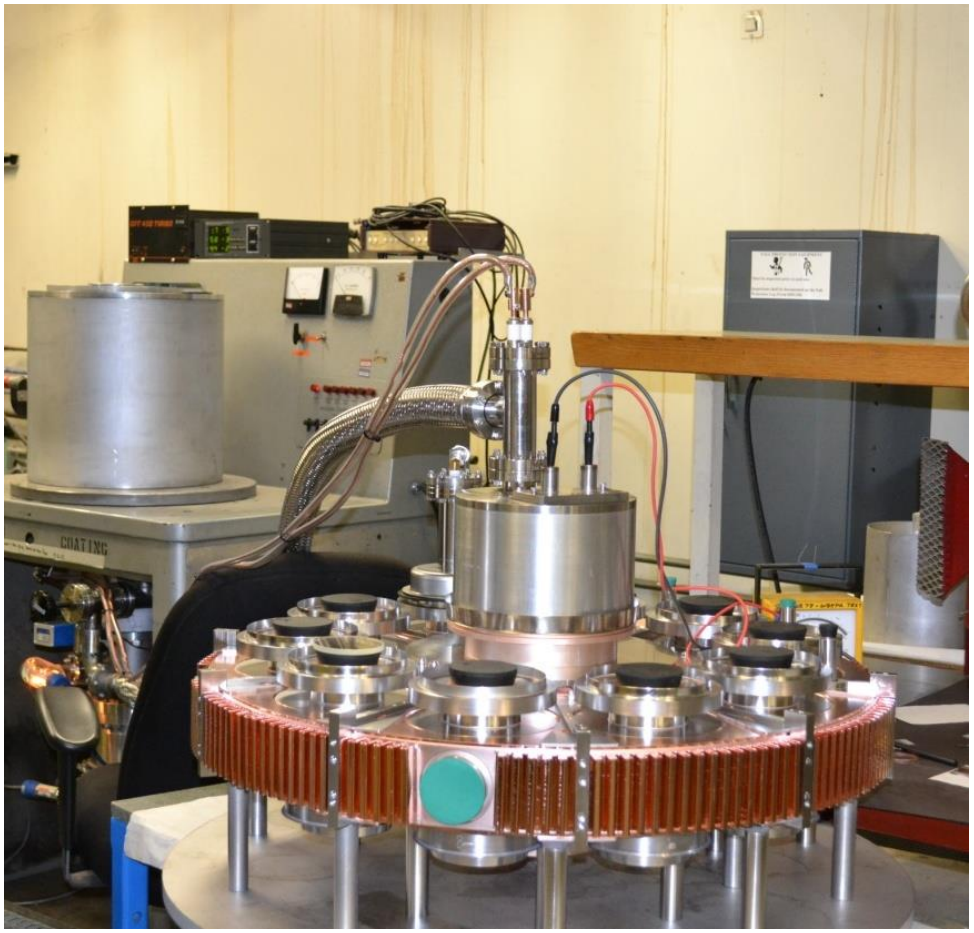


L-3 L6200 Multi-Beam IOT for ESS
Multipactor Prevention

- Simulations performed by L-3 Electron Technologies using Spark3D, a particle tracking code, indicated that, if left bare copper, the coaxial output would be susceptible to multipactor at operating power levels
- With TiN coating, multipactor threshold is > 10 MW


Before

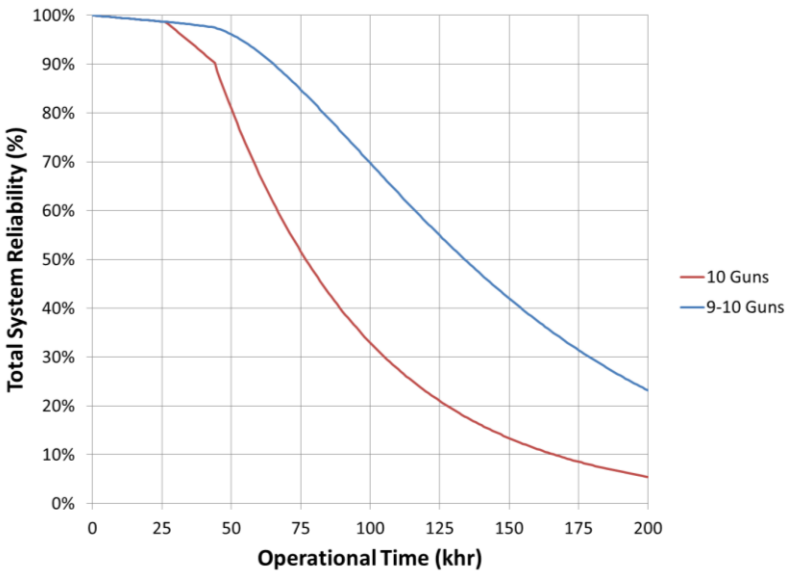

After



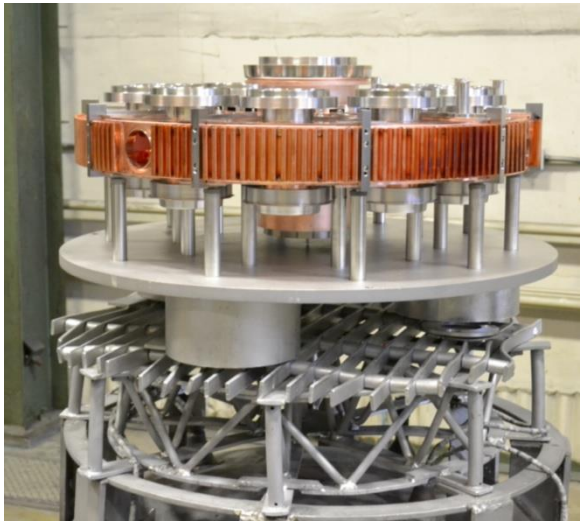
TiN coating applied to vacuum portion of coax to reduce secondary electron yield

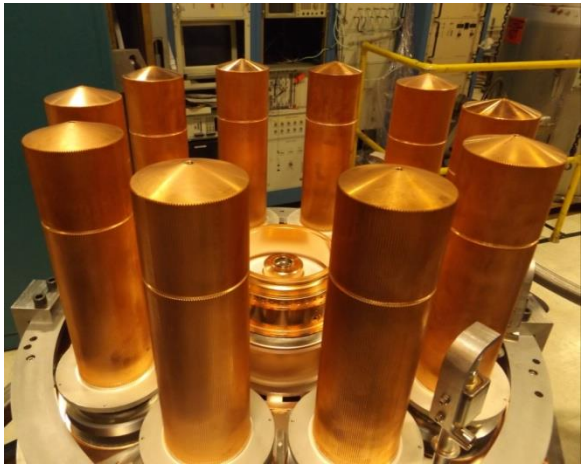
L-3 L6200 Multi-Beam IOT for ESS
Reliability and System Life Expectancy

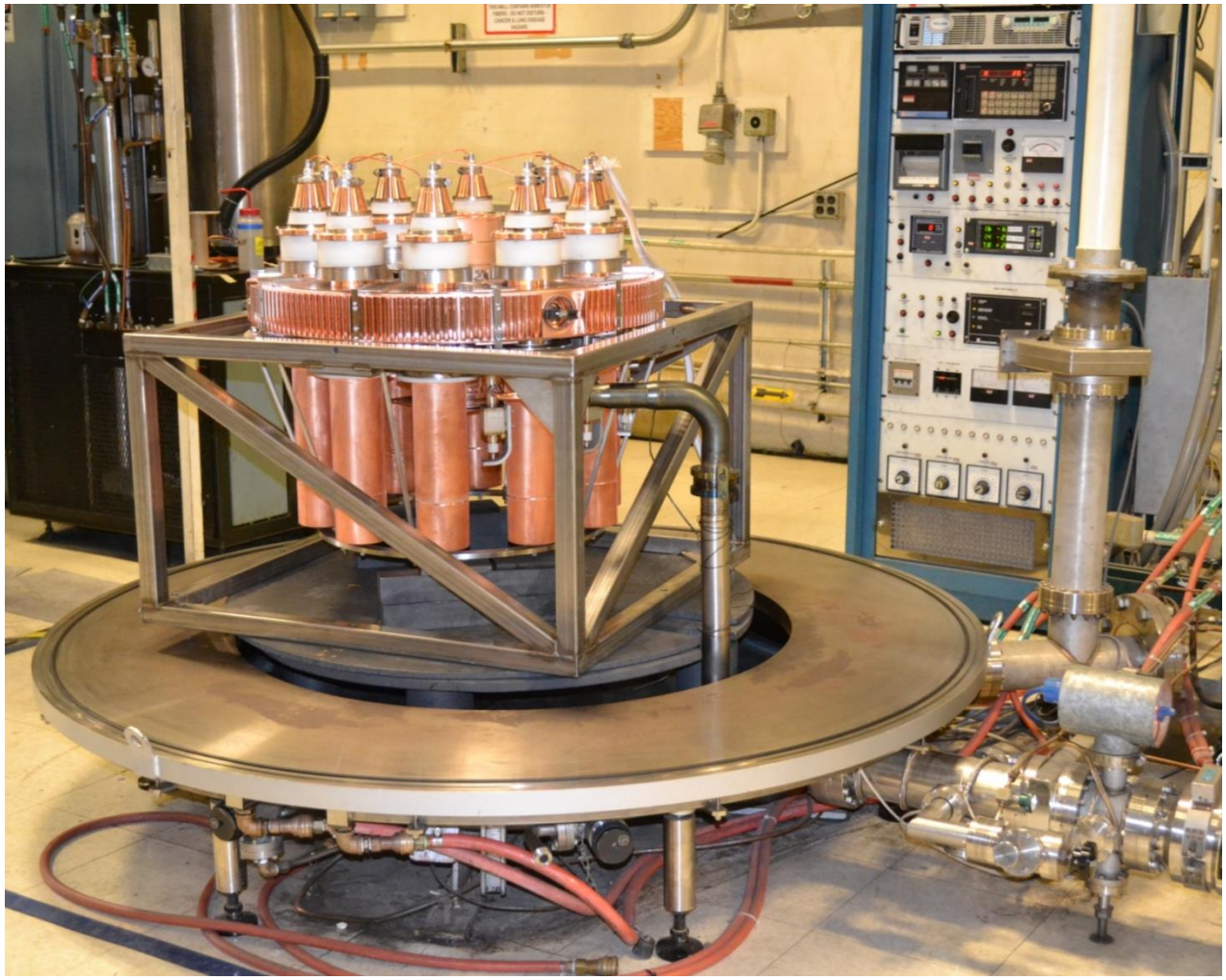
- From a reliability perspective, the main difference between a typical accelerator klystron and an IOT is that the latter uses a gridded, rather than cathode pulsed, gun
- The MBIOT leverages gun & collector designs of the proven L-3 broadcast tube
  - Hundreds of broadcast tubes have been produced, with extensive field data
  - IOT design and operation has been optimized to achieve operational life **> 8 yrs.**
- MBIOT design meets full RF spec performance with < 10 operational beams
  - In the unlikely event that a problem does develop, a gun can be taken offline by removing the associated HV cable
- Probability of survival vs. operating time
  - Calculated from field data, assuming occasional filament adjustments
  - No broadcast tube guns failed in < 3 years; random failures are extremely rare
- 10-gun array: **MTBF = 93 khr**
- 9 or 10-gun array: **MTBF = 150 khr**



L-3 L6200 Multi-Beam IOT for ESS
Assembly and Exhaust



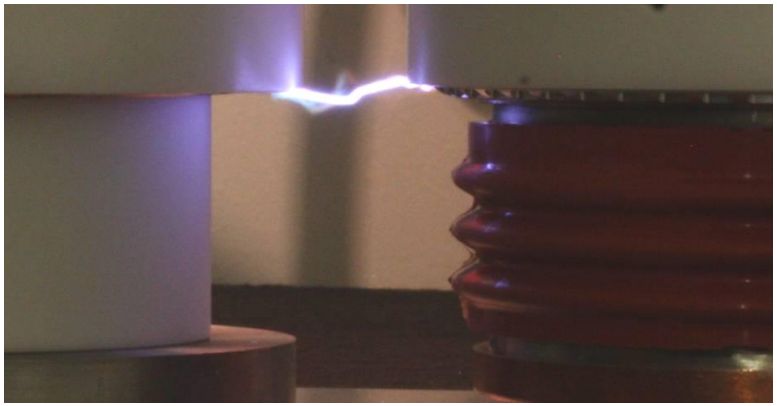




L-3 L6200 Multi-Beam IOT for ESS Final Fittings

Gun insulators potted with RTV

- Earlier voltage standoff tests conducted to 70 kV



- MBIOT guns were hi-potted to 50 kV

L-3 L6200 Multi-Beam IOT for ESS
Factory Test – Power Supply

Air-insulated Crowbar

Power Transformer

33 µF Capacitor Bank

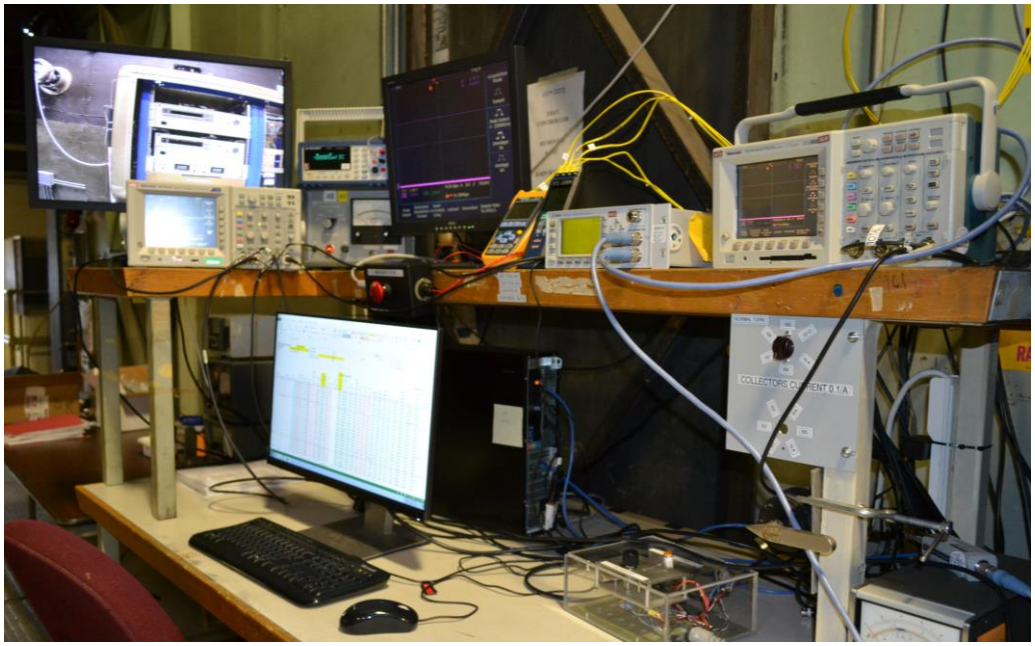
- Permanent MBIOT test facility has been assembled at L-3
  - High voltage power supply designed for 50 kV, 50 A peak
  - Cap bank sustains peak current during 4 ms long pulse
  - Crowbar design from SLAC B-factory klystron modulator
  - HV deck provides heater power and grid bias and is configured to allow individual guns to be taken offline

HV Deck

L-3 L6200 Multi-Beam IOT for ESS
Power Supply Features

- Capacitor bank initially 3 µF for short pulse operation (100 µs)
  - Expandable to 33 µF
- Heater current set identically for all guns
  - Two power supplies used for expediency due to kVA limitation of isolation transformers
- Grid bias supplied by single power supply
  - Each circuit is fused to isolate it in the event of a grid short
  - Grid interlock board fires crowbar in an under voltage condition to prevent gun from emitting CW
- Beam intercept and HV arc current are sensed through a 1 ohm resistor array separating the power supply from ground
  - Crowbar fires when voltage threshold is exceeded

L-3 L6200 Multi-Beam IOT for ESS Test Facility



Tomco Technologies 704 MHz solid state pulsed RF amplifier: 15 kW peak power, 4 ms pulses at 10% duty

Several tube diagnostics are available during operation:

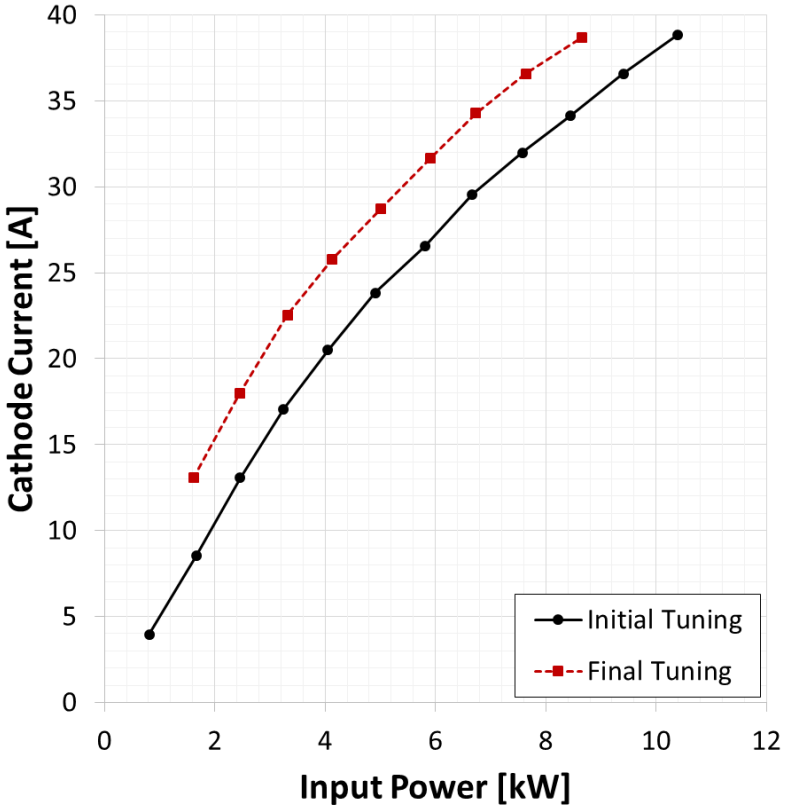
- 10k:1 HV divider
- Individual collector currents
- Total body current
- Total cathode current
- Forward / reflected power meters
- RF crystal detector
- Ion pump current
- Thermocouples at three locations

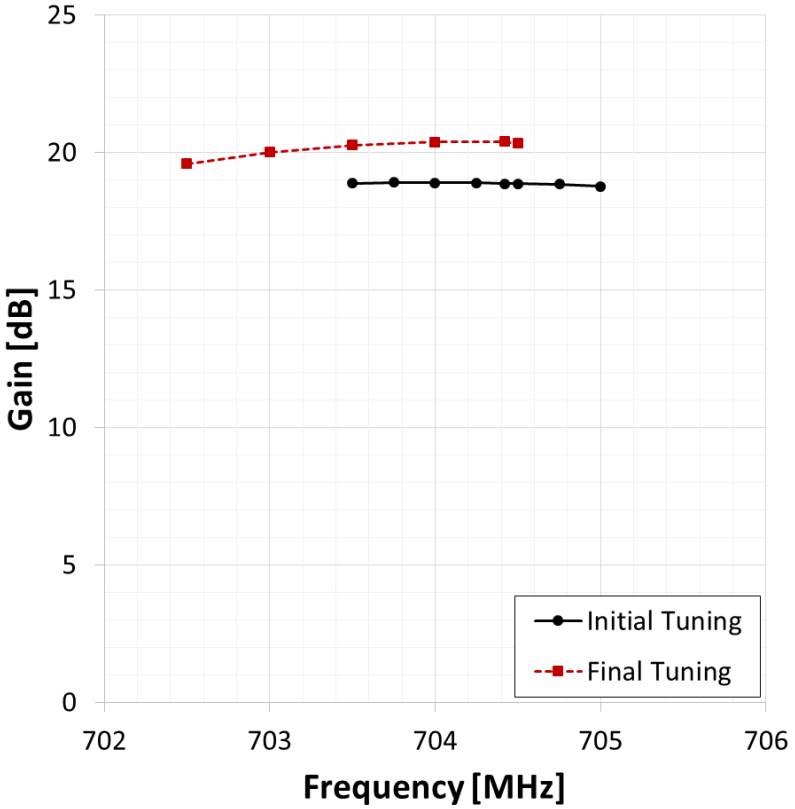
L-3 L6200 Multi-Beam IOT for ESS
Tube under Test

L-3 L6200 Multi-Beam IOT for ESS
Test Results - Tuning

- Guns brought online one-by-one
  - Associated collector current maximized by adjusting the coupling loop position and tuning the input cavity
- Line stretchers were initially used to optimize the phase of each drive line for maximum peak output power
  - Performance proven to be insensitive to small phase changes
  - Line stretchers were removed, as they are not required
- Output cavity tuned for maximum power at 704.42 MHz
- Output cavity Q adjusted to limit beam intercept current when the tube is operated at maximum drive

L-3 L6200 Multi-Beam IOT for ESS
Test Results – Gun Efficiency and Gain

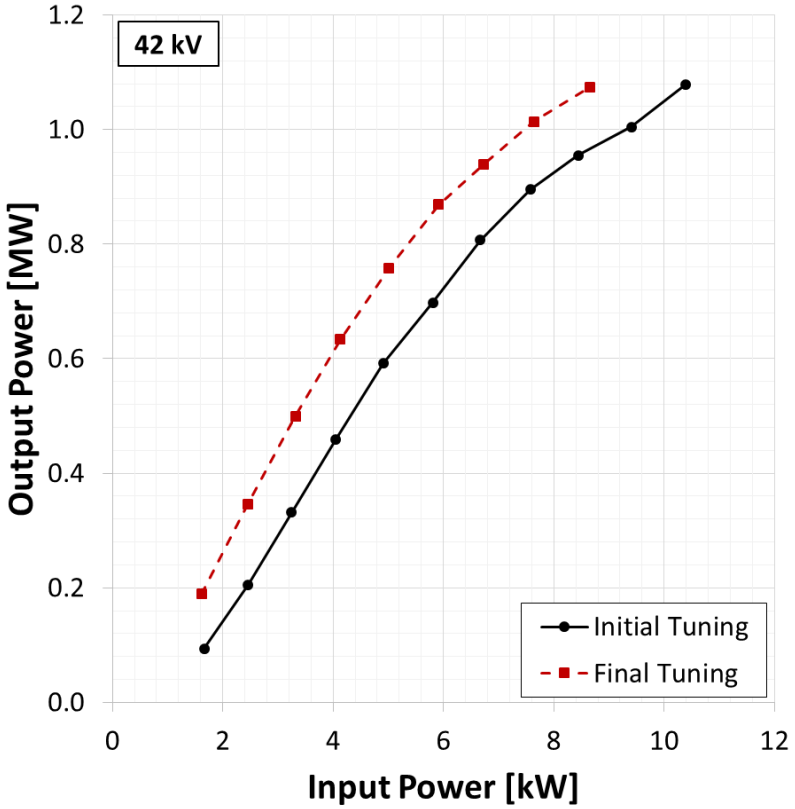


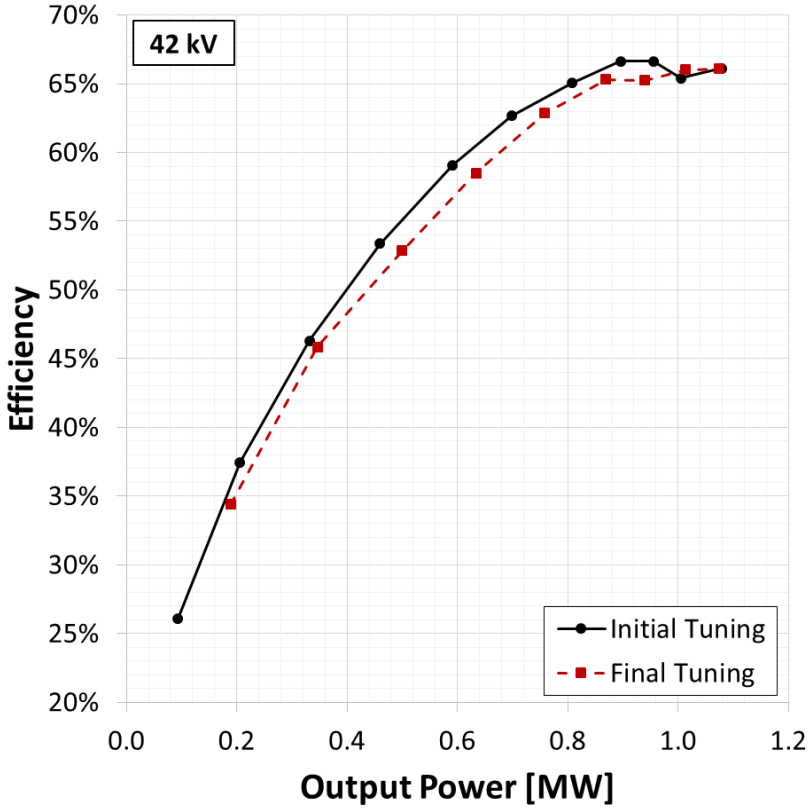


- Gain determined by gun efficiency: total beam current vs. RF drive power
- Grid bias reduced from 200 V to 160 V

- Idle current < 200 mA in both cases
- Gain increased after tuning of input cavities and adjusting grid bias
- Frequency centered around 704 MHz

L-3 L6200 Multi-Beam IOT for ESS
Test Results – Power and Efficiency vs. Tuning

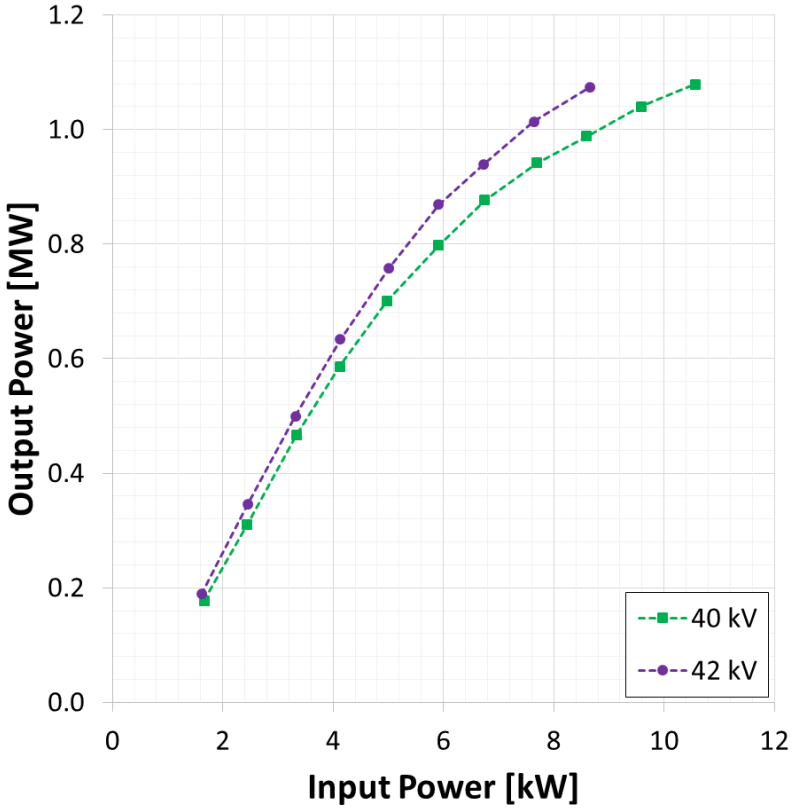


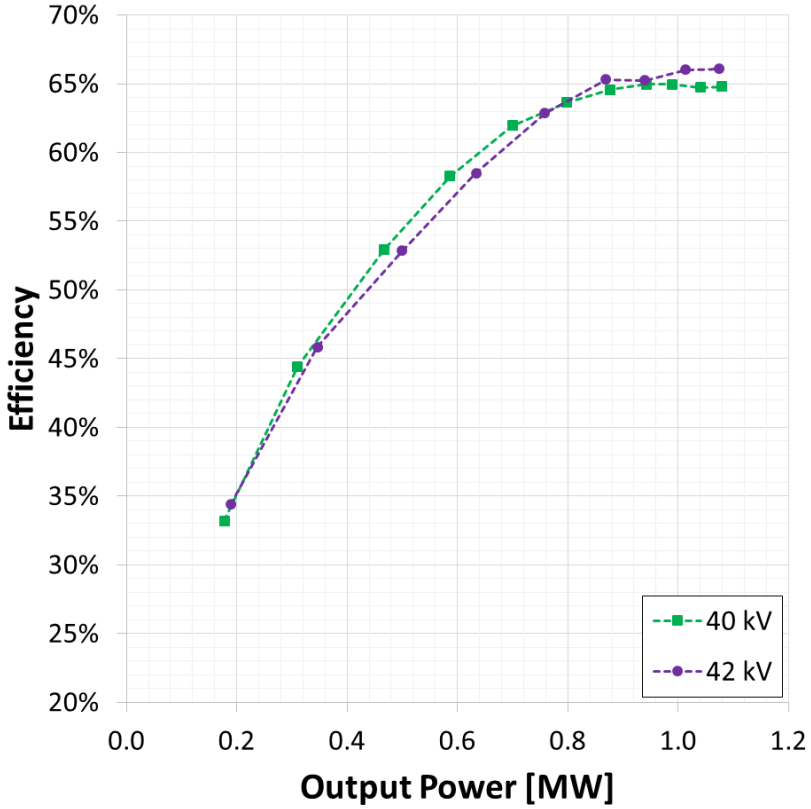


- Output was tuned to maximize power
- Grid bias was optimized to increase large signal gain

- Output Q was initially too high; efficiency rolled off at ~900 kW
- After minor reduction in Q, efficiency continues to increase above 900 kW

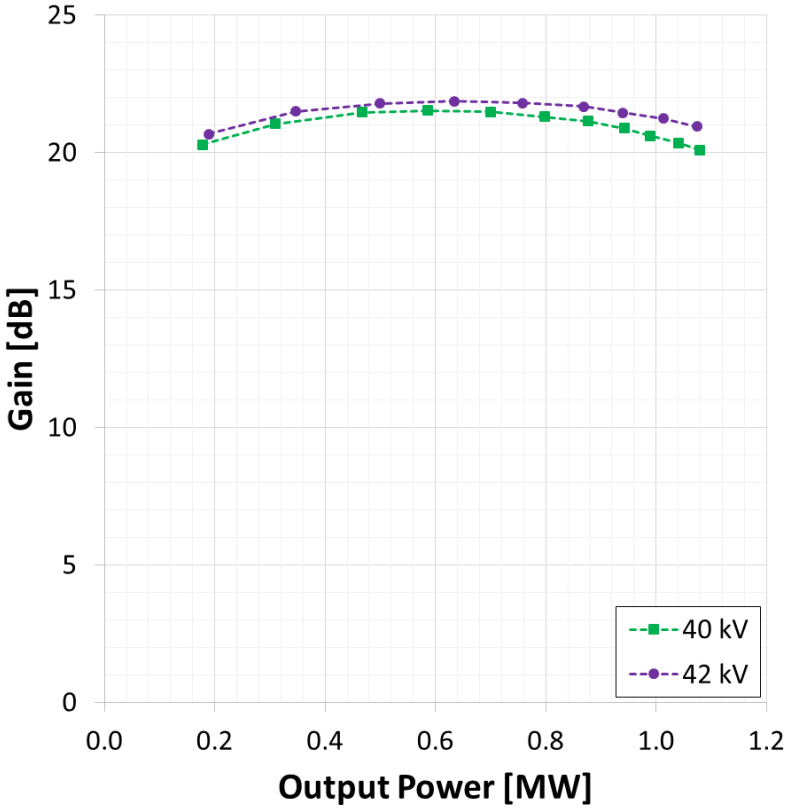
L-3 L6200 Multi-Beam IOT for ESS
Test Results – Power and Efficiency vs. E_k

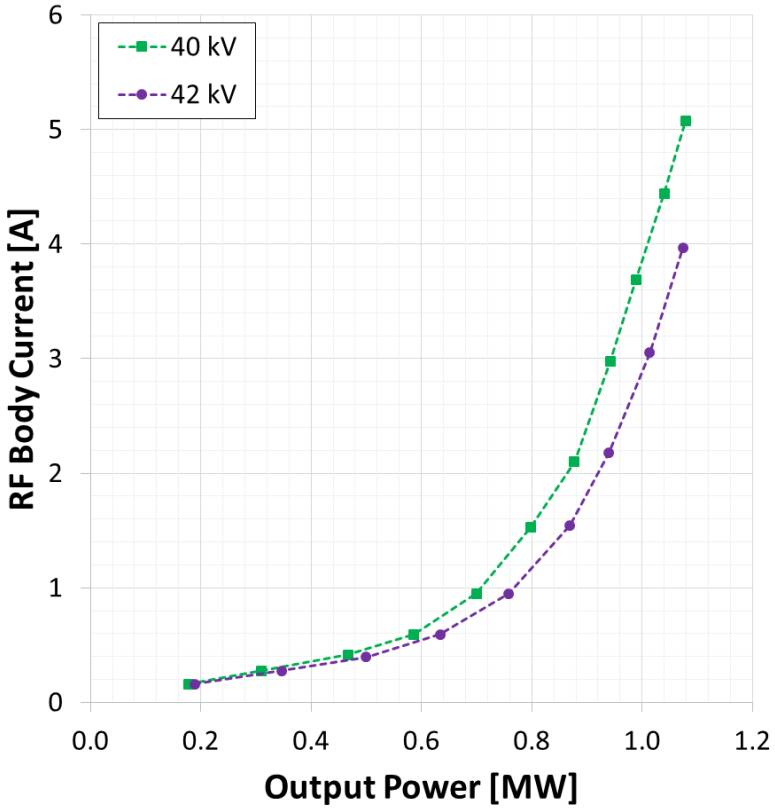




- With a fixed tuning, grid bias, and output Q, large signal gain increases with voltage
- As voltage increases, the peak efficiency increases, and occurs at higher output power levels

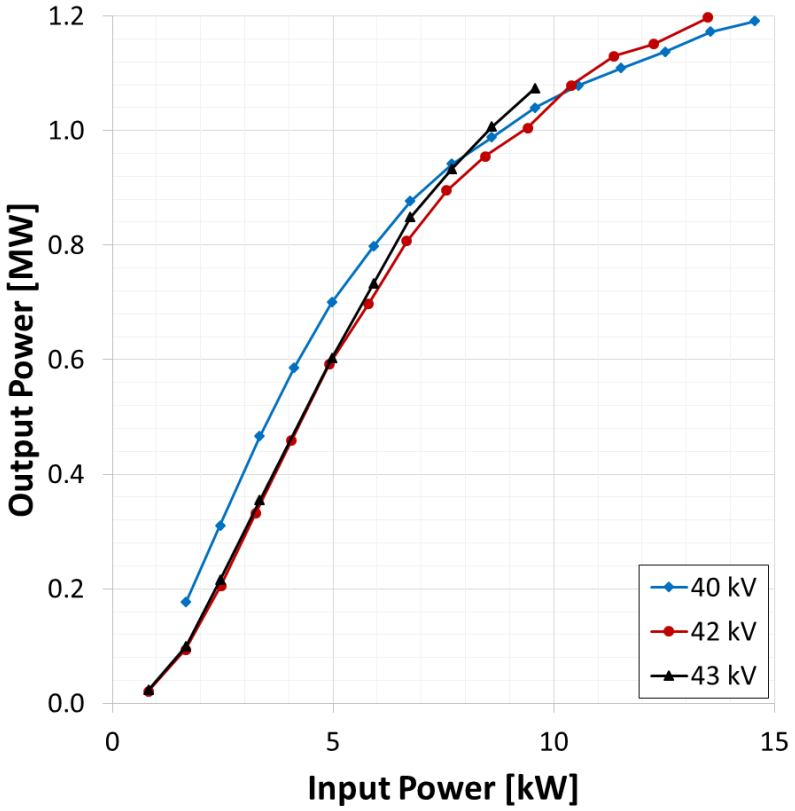
L-3 L6200 Multi-Beam IOT for ESS
Test Results – Gain and Bandwidth

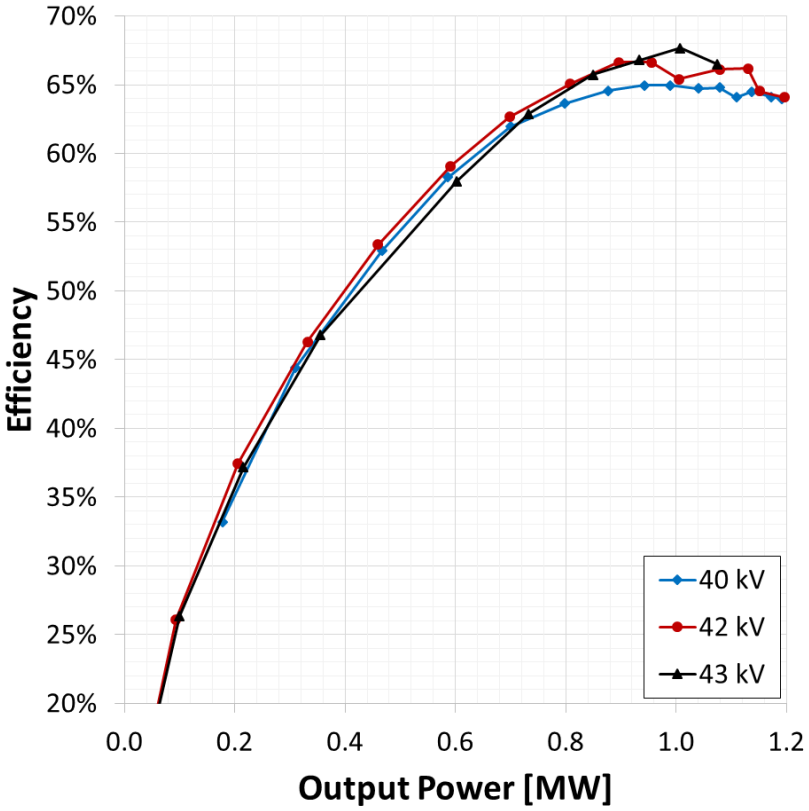




- 20 dB gain readily achieved at power levels up to 1 MW
- At full power, focusing improves substantially as voltage is increased

L-3 L6200 Multi-Beam IOT for ESS
Test Results – RF Performance





- Maximum output power of 1.2 MW was achieved at 40 and 42 kV

- Efficiency is maintained above 60 percent from 600 kW to 1.2 MW
- 68% efficiency demonstrated at 43 kV

L-3 L6200 Multi-Beam IOT for ESS
Test Results - Highlights

- The L6200 MBIOT has met key ESS requirements
- Power of 1.2 MW was demonstrated at 40 and 42 kV
- Efficiency remains above 60% from the 1.2 MW power level down to 650 kW, and can be optimized with Q tuning and voltage
- Efficiency of 68% was achieved
- Gain over 20 dB was demonstrated at most power levels, with maximum gain of 21.9 dB
- Tube conditioned to 4 percent duty at 750 kW
- Currently processed for voltages up to 43 kV; testing is ongoing
- No evidence of multipactor or spurious emissions observed

L-3 L6200 Multi-Beam IOT for ESS Conclusion

- Factory test of the L6200 1.2 MW 704 MHz peak power multi-beam IOT for the European Spallation Source is underway
- Improved efficiency, gain, and focusing is expected at higher voltage with Q tuning
- Power supply improvements are underway to allow operation at increased voltage and duty
- We would like to thank Morten Jensen and ESS for the opportunity to partner in the creation of this exciting new technology which, given its many advantages, has the potential to replace klystrons and MBKs in many high power UHF and L-band accelerator applications

L-3 L6200 Multi-Beam IOT for ESS
The Team