Medium Beta Klystrons and MBIOT prototypes update

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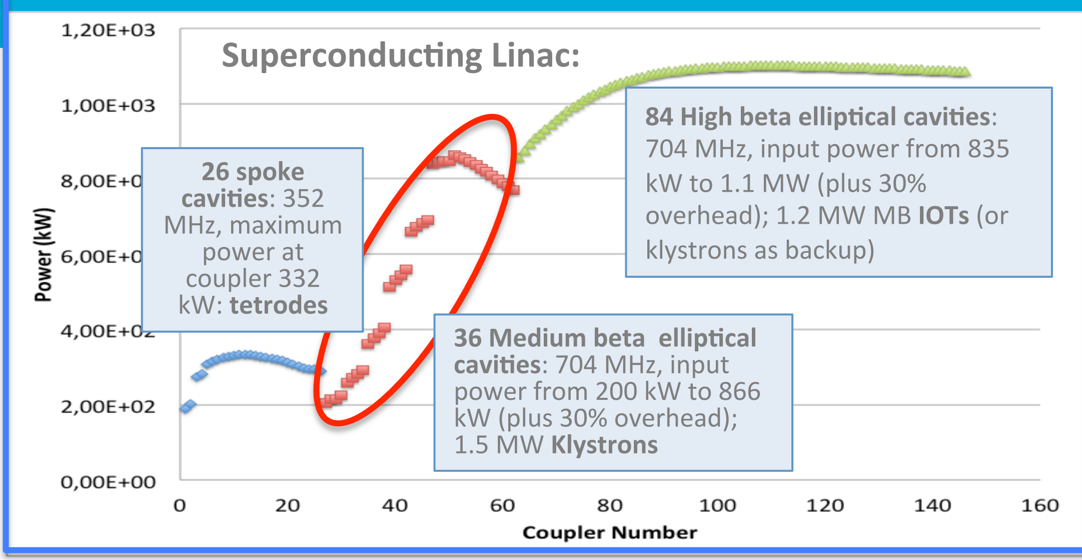
ESS

Overview

- RF amplifiers for the ESS Medium and High beta linac
- First Medium Beta klystron prototype (Toshiba) tested and delivered to Lund
- Update on the Thales and CPI medium beta klystron prototypes
- L-3 MBIOT first results
- Thales/CPI IOT update

ESS medium and high beta linac



Klystron specifications

Nominal output power	1.5 MW
Frequency	704.42 MHz
Bandwidth	≥ +/- 1 MHz
Pulse length	3.5 ms
Repetition rate	14 Hz
Efficiency	>60%
VSWR	Up to 1.2
Power Gain	≥ 40 dB
Group Delay	≤ 250 ns
Harmonic Spectral content	≤ -30 dBc
Spurious Spectral content	≤ -60 dBc

IOT specifications

Peak output power	> 1.2 MW
Frequency	704.42 MHz
Beam voltage	< 50 kV
Beam current	< 45 A rms
Pulse length	3.5 ms
Duty factor	Up to 5%
-1dB bandwidth	> 2 MHz
Gain	> 20 dB
RF efficiency	> 65%
Overall efficiency (including idle current)	> 60%
Tube life	>= 50 khrs

Medium beta klystron prototypes

Three prototypes procured:

- Thales (contract placed in January 2015)
- Toshiba (contract placed in February 2015)
- CPI (contract placed in April 2015)

Contract duration: 15 months

Klystron specifications

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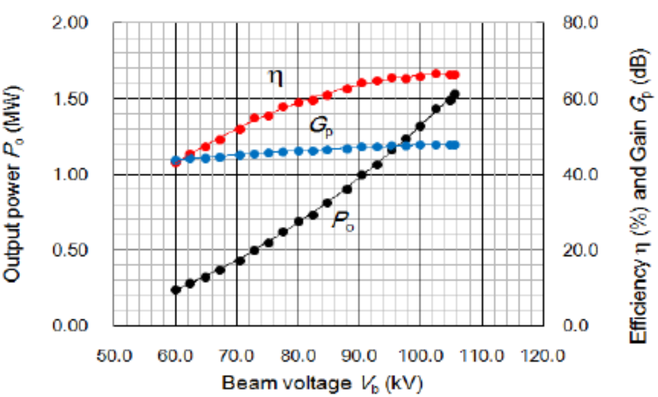
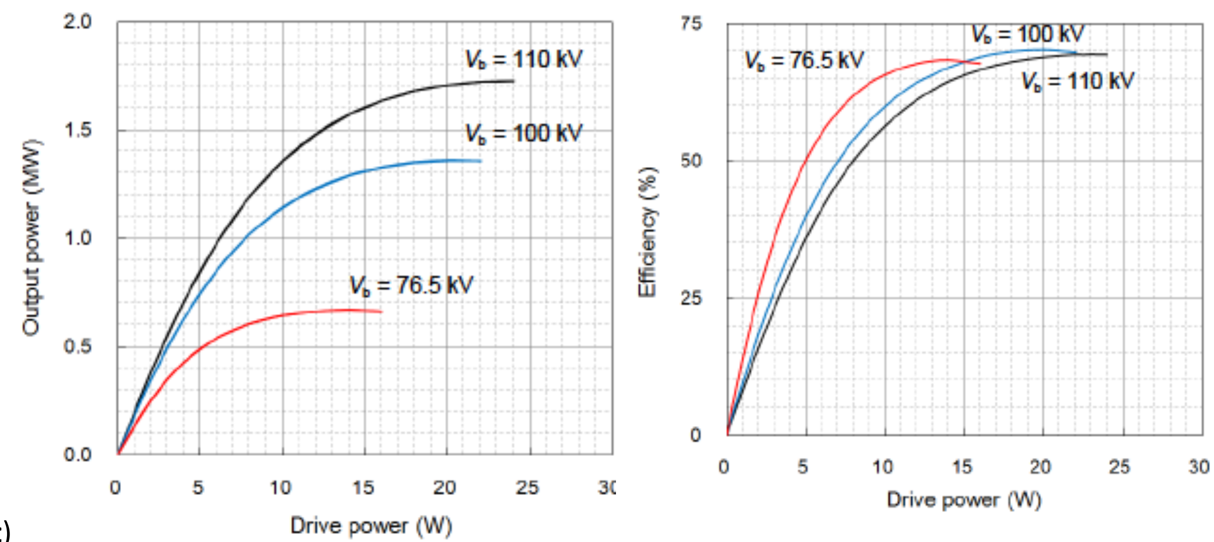
Medium Beta klystrons: main design features

- “Standard” klystron design with 6 cavities including three gain cavities and one second harmonic
- Target efficiency 65% (saturated)
- FUG filament power supply (HF trasformer in the oil tank + low voltage unit) + current limiting resistors
- Collector designed to operate with a cooling water temperature up to 60 °C.
- Two arc detection systems can be used (CERN/Microstep and AFT)

The external Q of the output cavity can be changed to increase the efficiency of the klystron when operating at low beam voltages; this is done by introducing a mismatch at the klystron output.
The use of the mismatch allows to keep nominal efficiency also at low power levels.



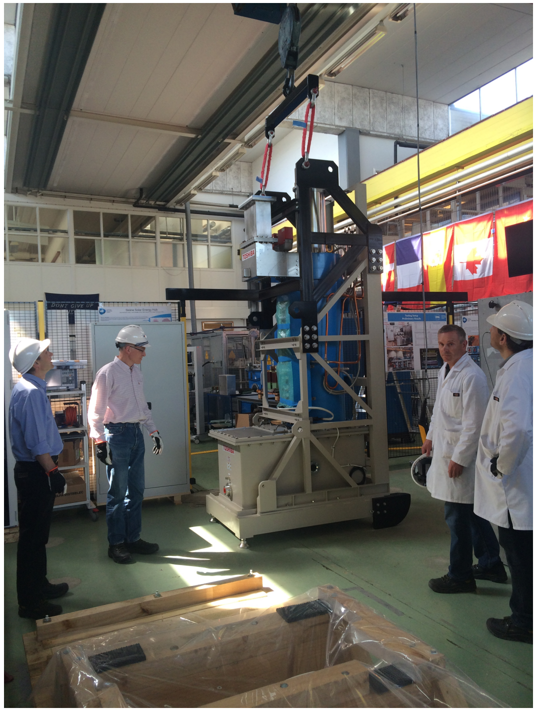
Measured data (**no mismatch used at the output**)
Courtesy of Toshiba



Simulated data: **the output match is modified** to keep high efficiency at reduced beam voltage (courtesy of Toshiba)

Toshiba klystron prototype E37504

- New development started in February 2015.
- The Toshiba klystron was tested at Factory in Japan in presence of ESS staff at the beginning of February.
- Delivery took place on March 16th, two months ahead of schedule.
- Klystron is now in place at the Lund Test Stand, ready to be tested



Toshiba klystron prototype E37504

EUROPEAN SPALLATION SOURCE

- Compact design: 3.5 m including collector and gun tank
- High gain (>47dB)
- High efficiency (65%)

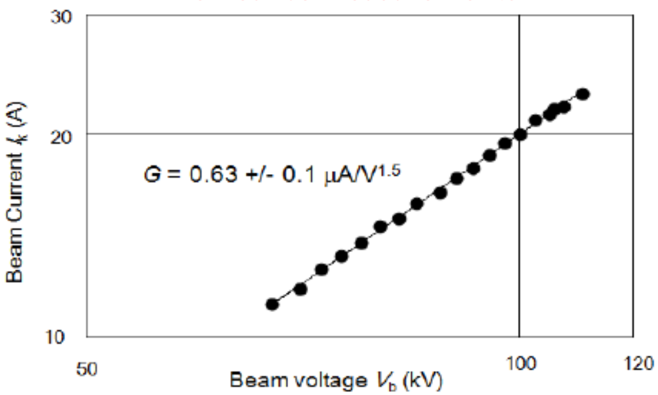
3.5 m

- ✓ Two electromagnet power supplies are required to provide current to the three focusing coils (one gun coil + two main coils):
- ✓ Dispenser cathode
- ✓ The output window is water cooled.
- ✓ The tube can operate at low beam voltages (<85 kV) keeping high efficiency by using an output mismatch (Iris)

Toshiba klystron prototype: test results

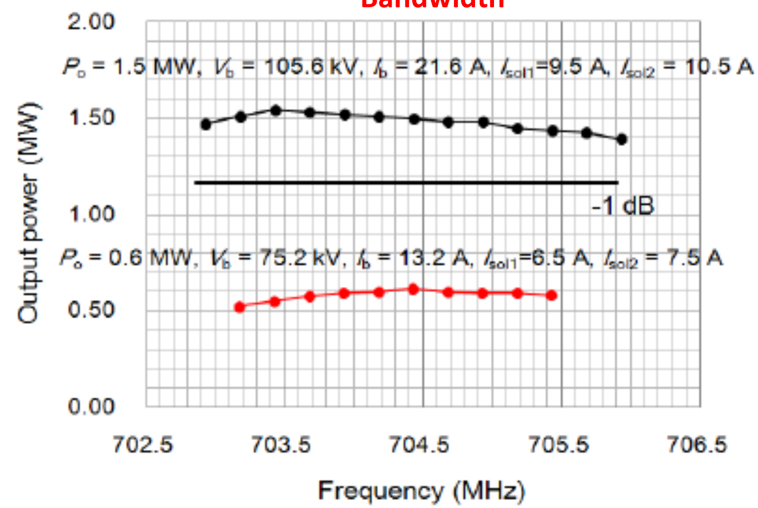
Some results from the **Factory Acceptance Test** (February 2016):

Perveance measurements

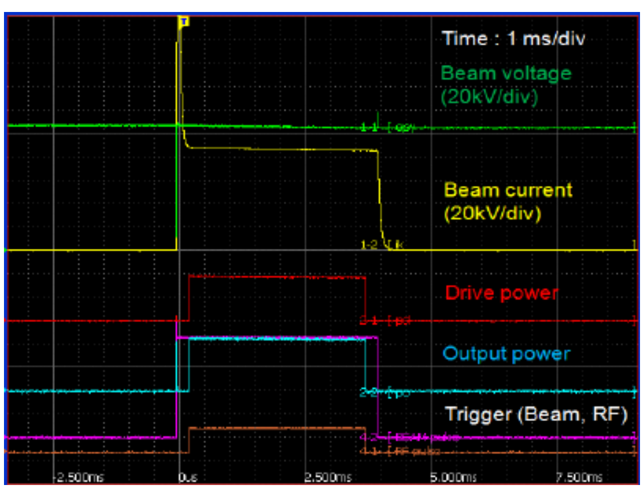


Beam pulse width 4.0 ms, Repetition rate 14 Hz (I_{sol1} = 9.5 A, I_{sol2} = 10.5 A)

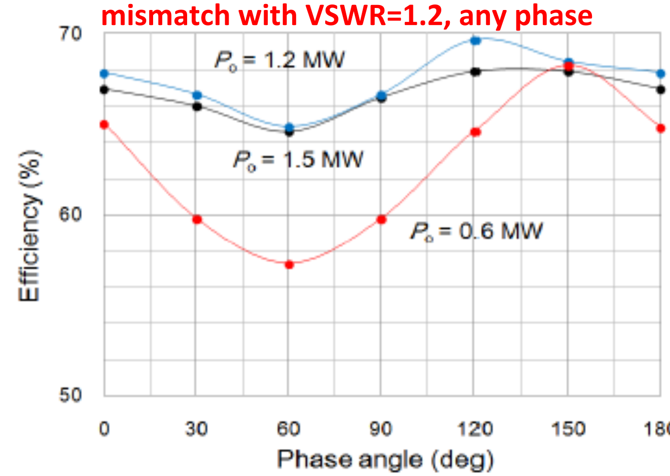
Bandwidth



Waveforms at 1.5 MW output power



Efficiency of the klystron when operating on a mismatch with VSWR=1.2, any phase



Courtesy of Toshiba

Toshiba klystron prototype: test results

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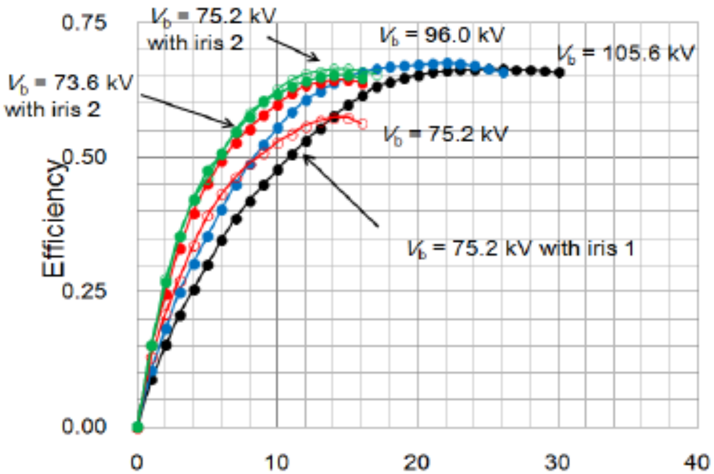
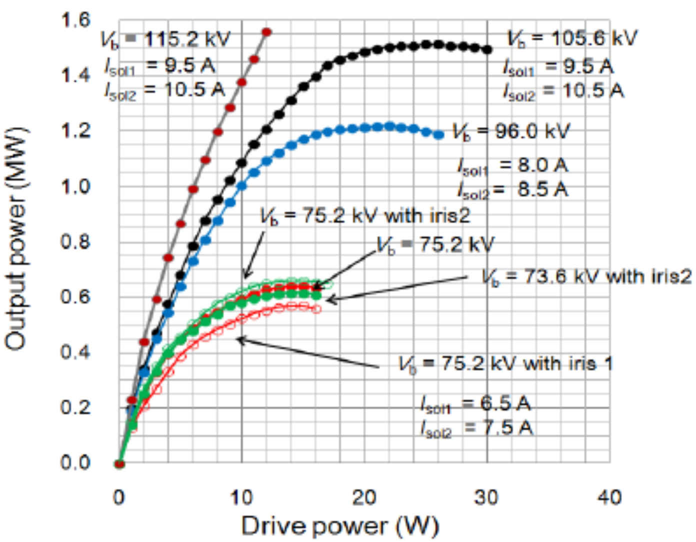
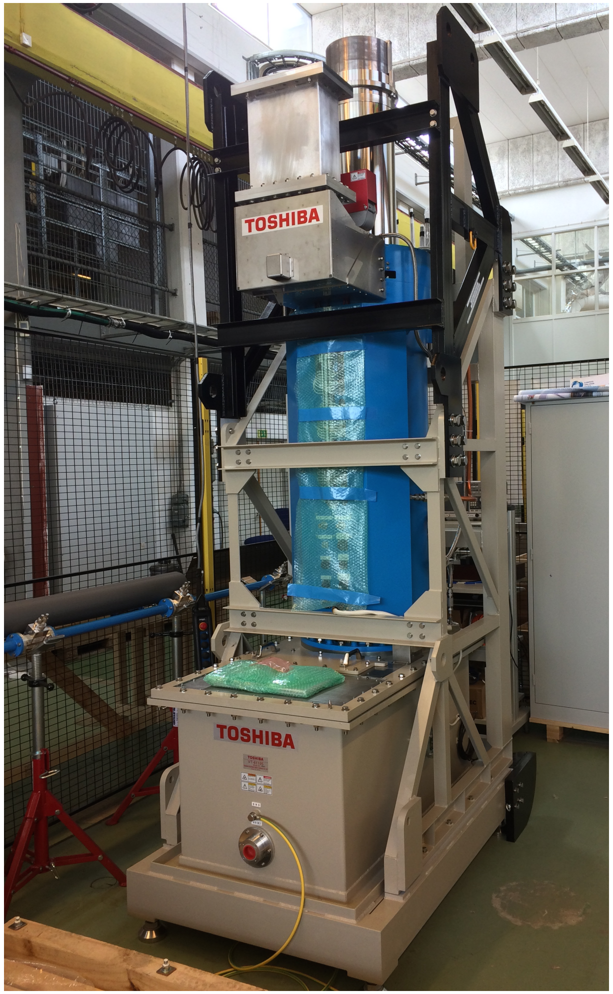




Courtesy of Toshiba

Efficiency and output power at nominal and at lower beam voltages with and without output mismatch

Klystron accepted and delivered to Lund!

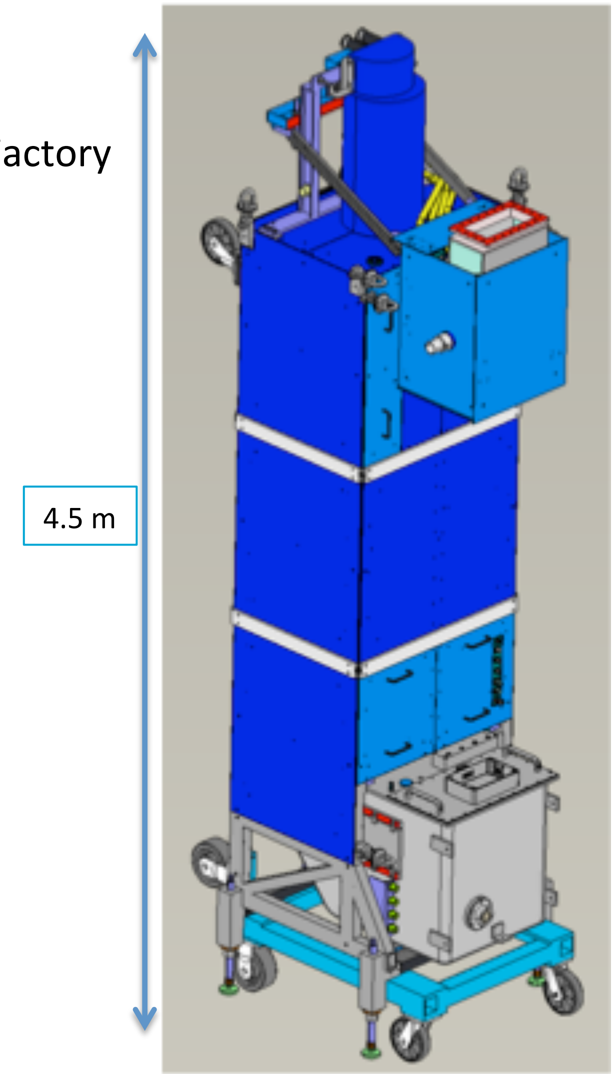


Thales klystron prototype TH2180

Based on the TH2182 developed for CERN (horizontal orientation)
Cern tube has been also tested at 1.7 ms, 2 Hz and 1.7 ms, 50 Hz (Factory Acceptance Test)

- High gain (>47dB)
- High efficiency (>65%)

- Two electromagnet power supplies are required to provide current to the two focusing coils
- The output window is air cooled.
- The tube can operate at low beam voltages keeping high efficiency by using an output mismatch. The mismatch is provided through a post that can be inserted on the output waveguide (external to the X-rays shielding). Different posts can be used to optimize the tube performance at any operating voltage.



Courtesy of Thales

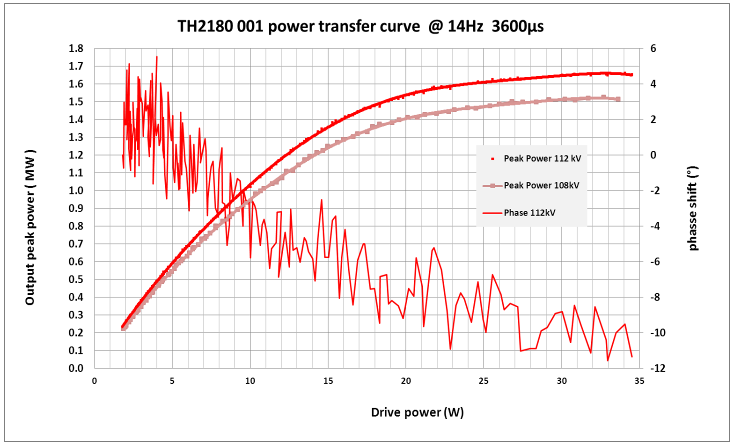
Thales klystron prototype TH2180

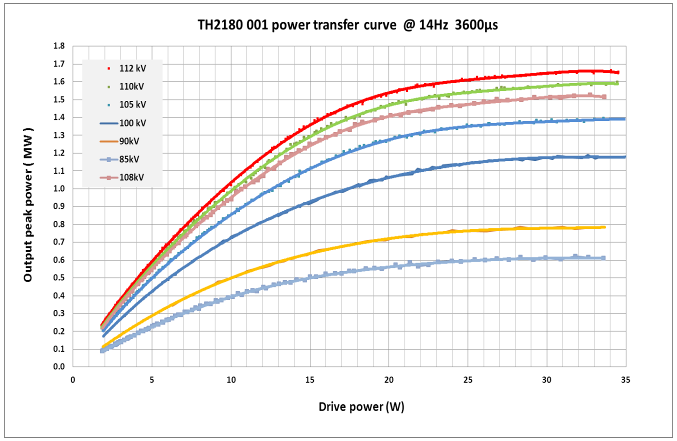
EUROPEAN SPALLATION SOURCE

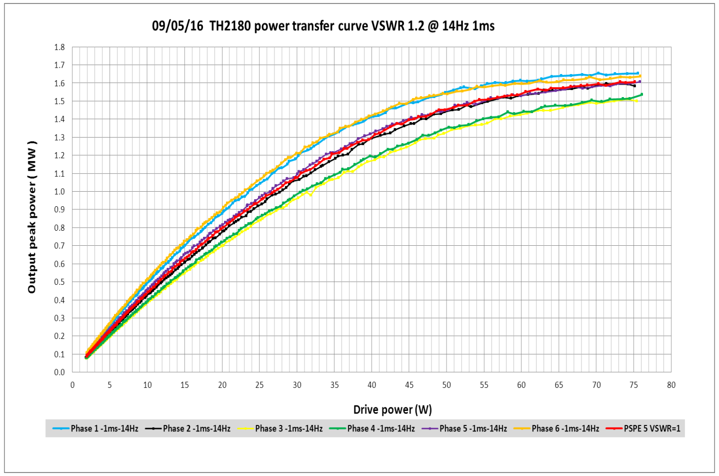
The tube has been tested at factory at full power for few days in May 2016.

Saturated efficiency 66%.

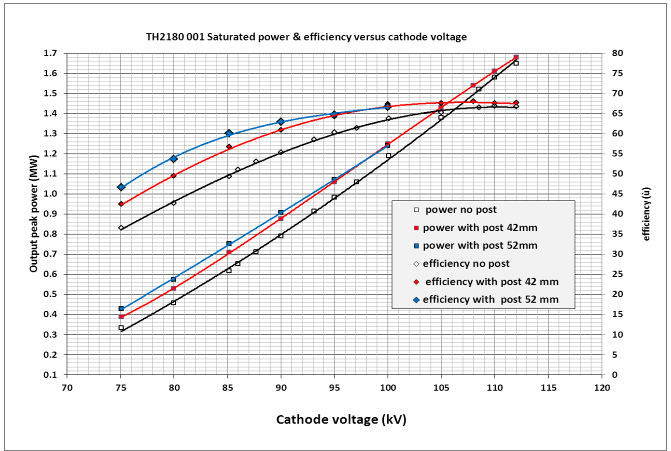
Courtesy of Thales





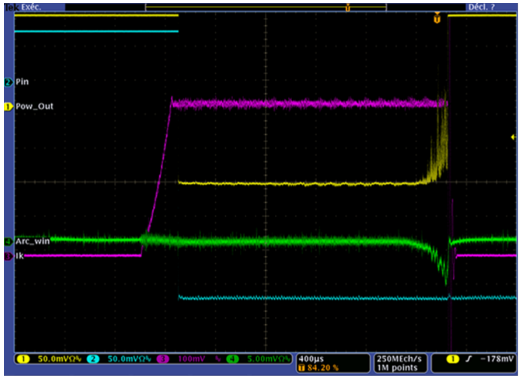


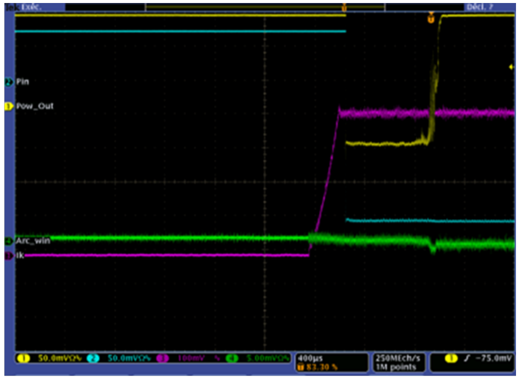
Operation at low beam voltage: efficiency can be increased by using a mismatch at the output (post). Preliminary results (can be improved):

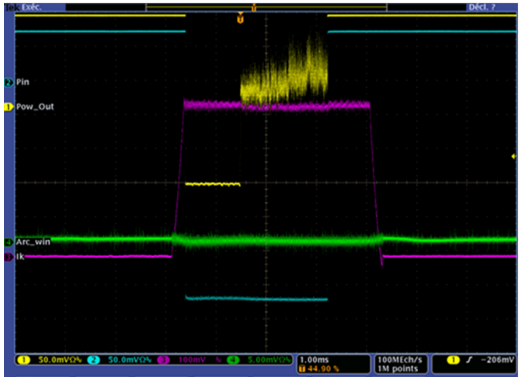


Thales klystron prototype TH2180

Factory Acceptance Test have not been performed yet due to problems arising in the RF output circuit:
When an event occurs, the RF output pulse is partially or completely truncated. In most cases, it gives rise to a vacuum trip, and in some case there is some light detected by the AFT arc detector pointing the window. The HV is switched off by vacuum interlock or by arc detector interlock. The problem is under investigation.







oscilloscope screenshots showing RF output pulse instabilities:
Yellow trace = RF output pulse
Blue trace = RF drive pulse
Purple trace = Beam current pulse
Green trace = AFT arc detector signal

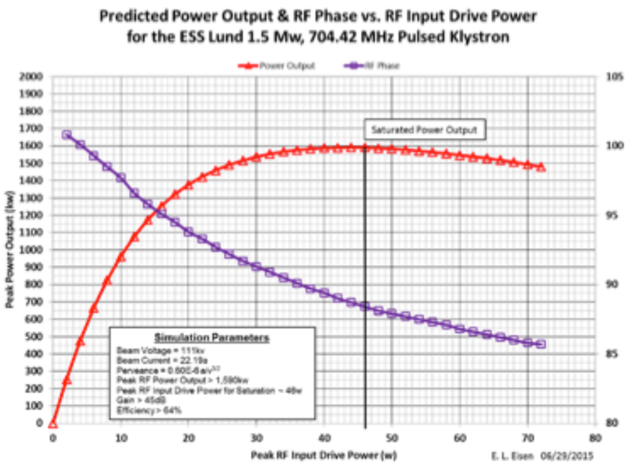
Courtesy of Thales

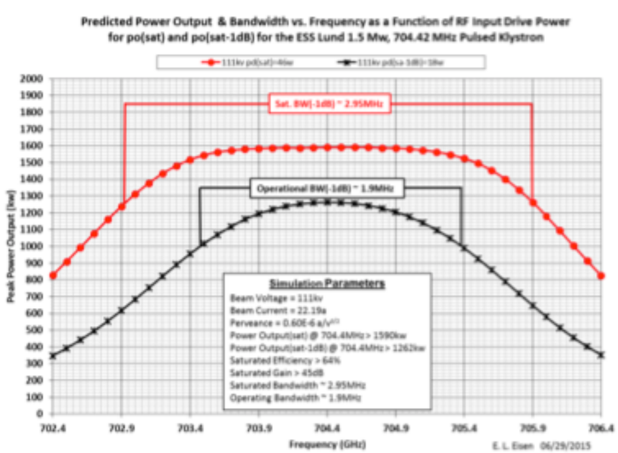
CPI klystron prorotype VKP-8292A

EUROPEAN SPALLATION SOURCE

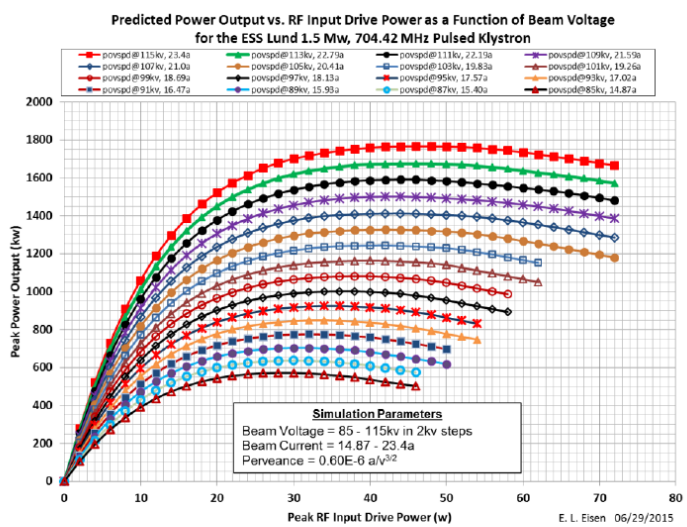
New development based on CPI experience from the SNS klystrons

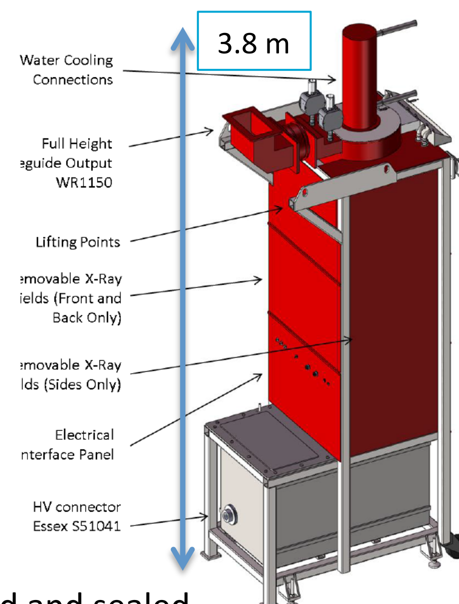
Simulated performances:





- Up to three electromagnet power supplies are required to provide current to the focusing coils
- The output window is air cooled.
- The tube can operate at low beam voltages keeping high efficiency by using an output mismatch.



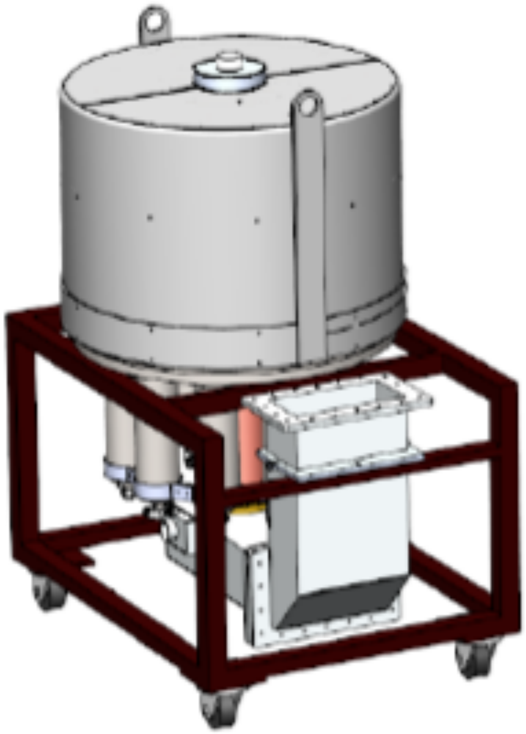


- The vacuum envelope has been assembled and sealed
- Testing will start mid-June
- Delivery expected in August 2016

Courtesy of CPI

MBIOT status

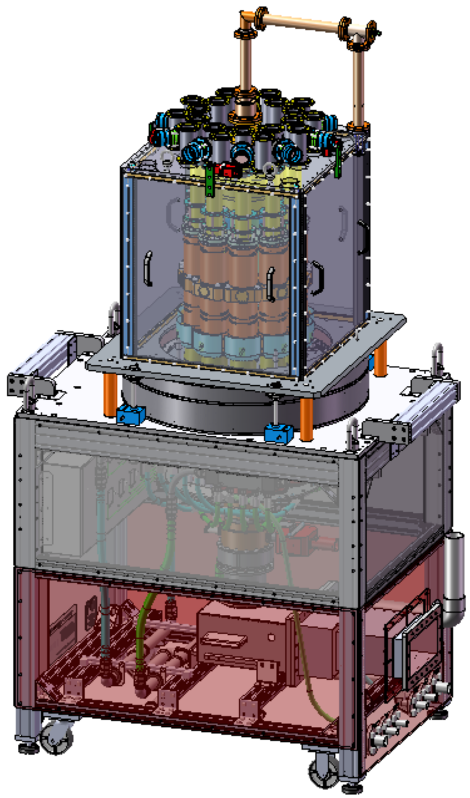
- MBIOTs are the baseline power sources for high beta linac.
- IOT beam power is proportional to the RF drive: no back off for regulation is needed, enabling higher operating efficiency with respect to klystrons.
- Two prototypes under development (L-3 and Thales/CPI consortium)



Courtesy of L-3

IOT specifications

Peak output power	> 1.2 MW
Frequency	704.42 MHz
Beam voltage	< 50 kV
Beam current	< 45 A rms
Pulse length	3.5 ms
Duty factor	Up to 5%
-1dB bandwidth	> 2 MHz
Gain	> 20 dB
RF efficiency	> 65%
Overall efficiency (including idle current)	> 60%
Tube life	>= 50 khrs

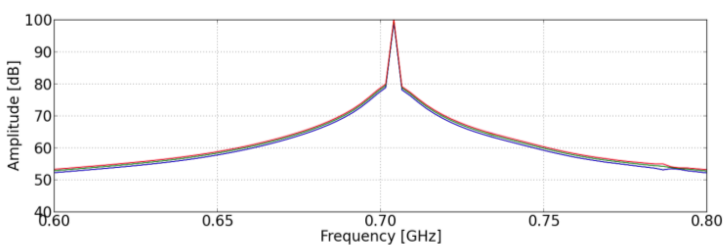


Courtesy of Thales/CPI

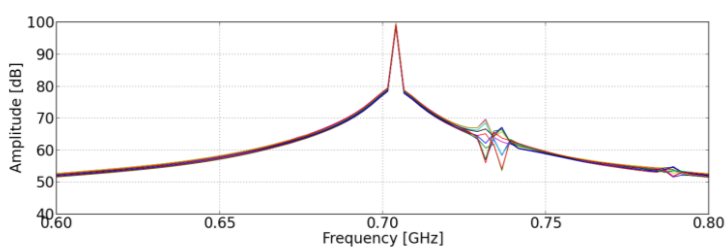
L-3 MBIOT L6200

- Ten electron guns
- Toroidal output cavity
- Ten individual collectors water cooled and rated for >35 kW DC
- Full RF performance is possible with less than 10 beams
- The output cavity is coupled to the output waveguide (WR1150) through a T-bar coax to waveguide transition. The coaxial window is derived from the SLAC 1.2 MW CW window used for the B-factory klystron.

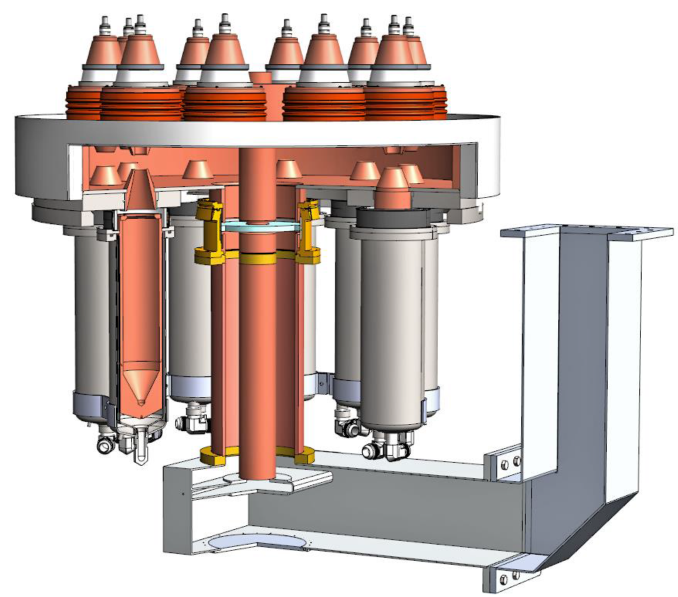
Several simulation tools used during the design. MAGIC3D used to analyze the performance in case of phase variation beam to beam, operation with less than 10 beams, stability and spurious output



Nominal case (identical beams)



When phase varies, HOMs are excited

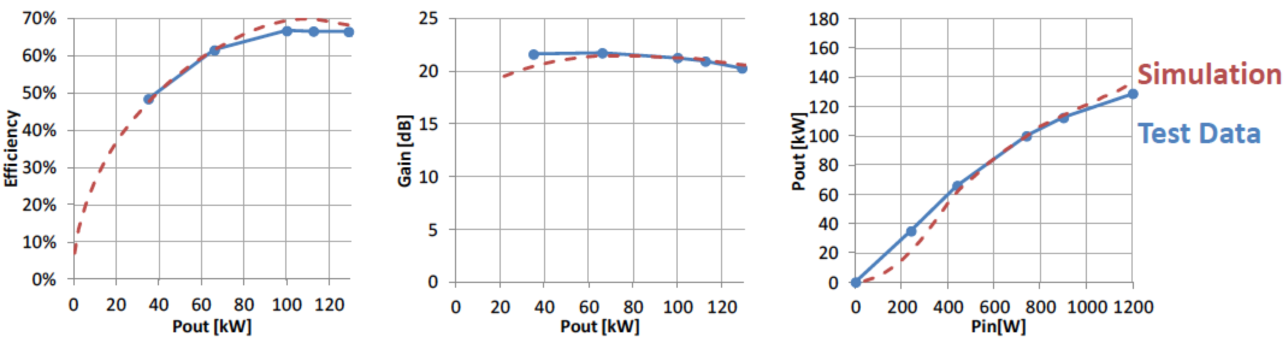


Courtesy of L-3

L-3 MBIOT L6200

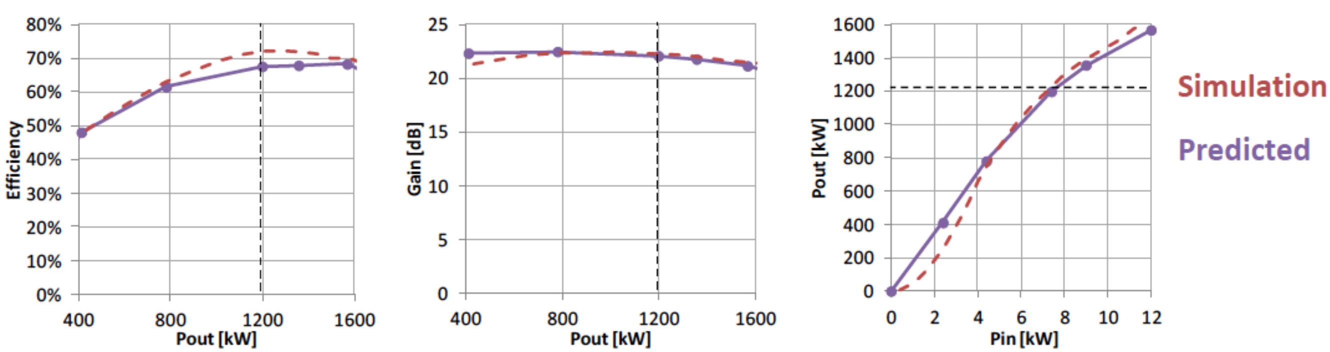
EUROPEAN SPALLATION SOURCE

Single beam IOT built in 2015 in order to validate the design tools and refine assembly procedures



SB Test result and simulations at 35 kV

Expected performance of the MB IOT from simulation and single beam test data at 45 kV



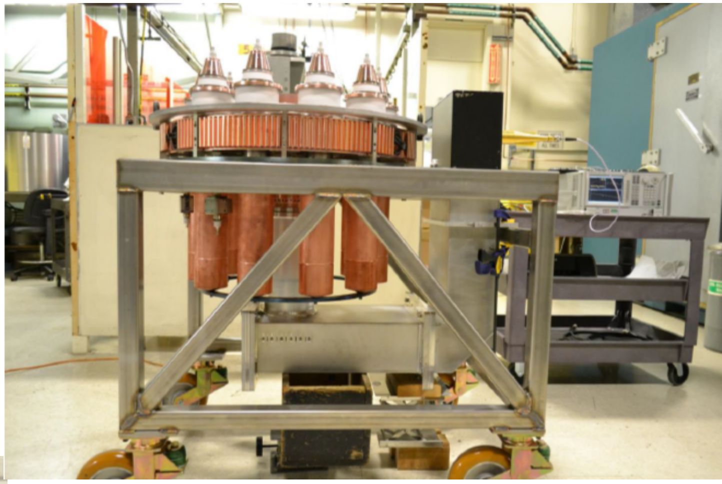
Single beam IOT and Tomco SS driver

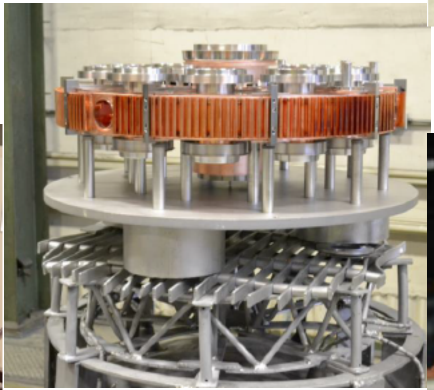
Courtesy of L-3

L3 MB IOT assembly and fabrication

Multibeam prototype assembled

- Output cavity frequency and Q_{ext} verified after exhaust
- Gun insulators potted with RTV: early voltage stand-off tests conducted at 70 kV
- MBIOT Hi-Potted to 45 kV





Courtesy of L-3

L-3 MBIOT

MBIOT currently under test at L3 facility:

- HV power supply (50 A, 50 kV peak)
- Capacitor bank to sustain peak current during the 4 ms pulse
- Crowbar design from SLAC
- HV deck to provide heater power and grid bias. Individual guns can be taken off line
- 704 MHz SS drive from Tomco, 15 kW peak power (4 ms pulses at 10% duty)

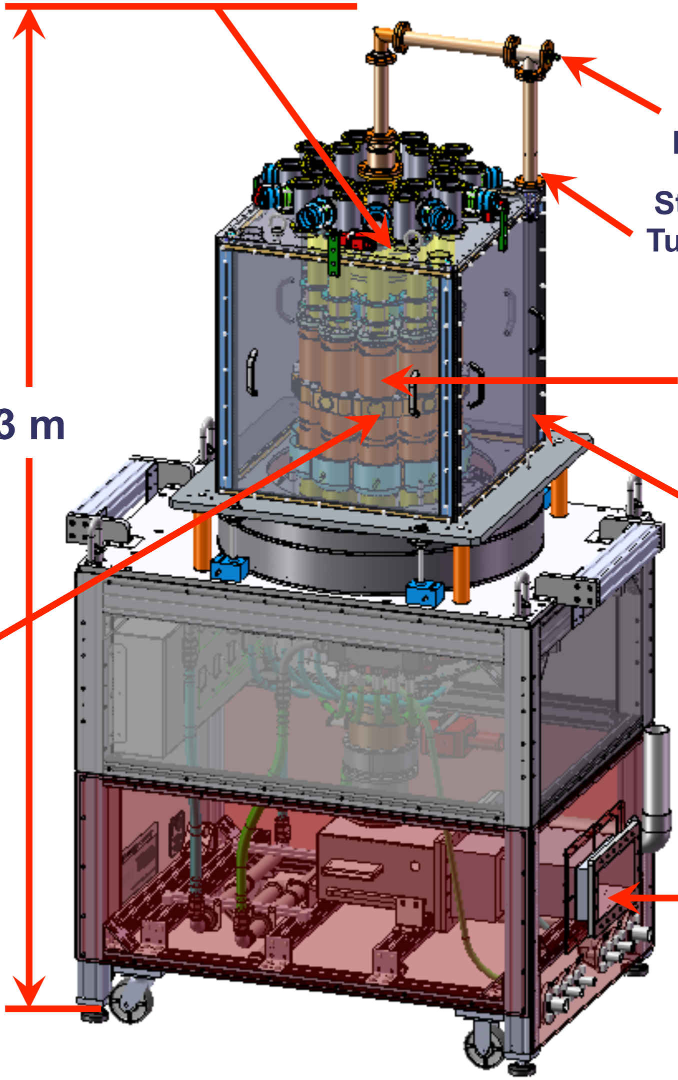
HV Deck

Air-insulated Crowbar

Courtesy of L3

Thales/CPI MB IOT

- Ten electron guns
- Single annular output cavity
- Ten individual collectors.
- Single RF input; single stub tuner to adjust overall match
- Custom RF splitter delivering balanced RF to the 10 guns
- 10 coax individual gun feeds (with tuning system for frequency and match)
- DC blocker (used up to 50 kV in CPI SBIOTs)

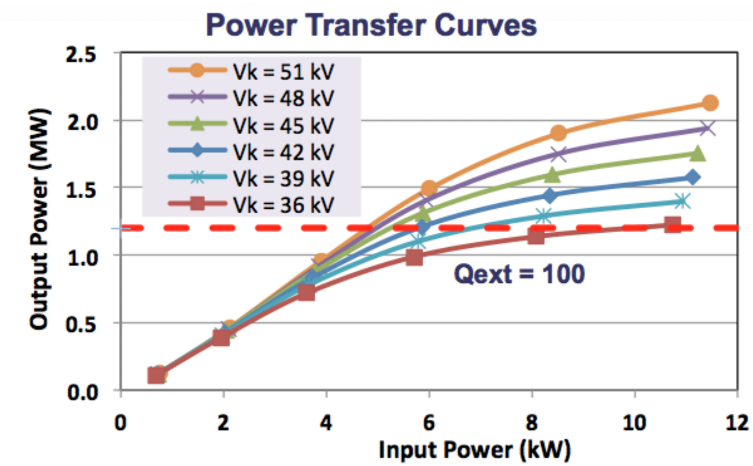


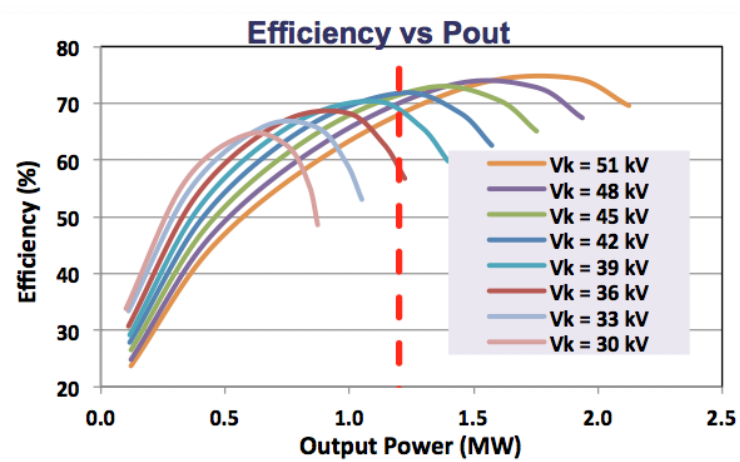
Foot print: 1.0 x 1.5 m
Height: 3 m
Weight: 1500 kg

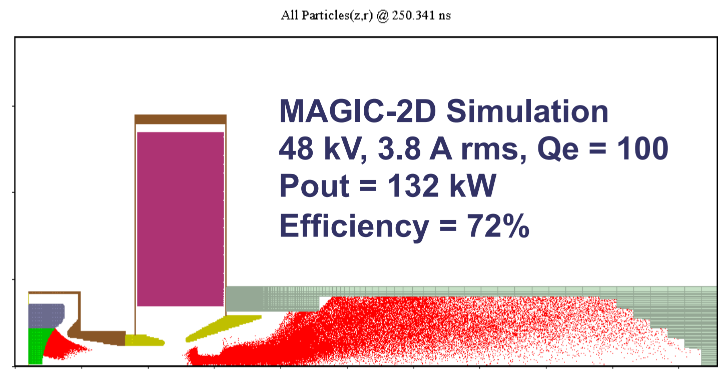
Courtesy of Thales and CPI

Thales/CPI MB IOT

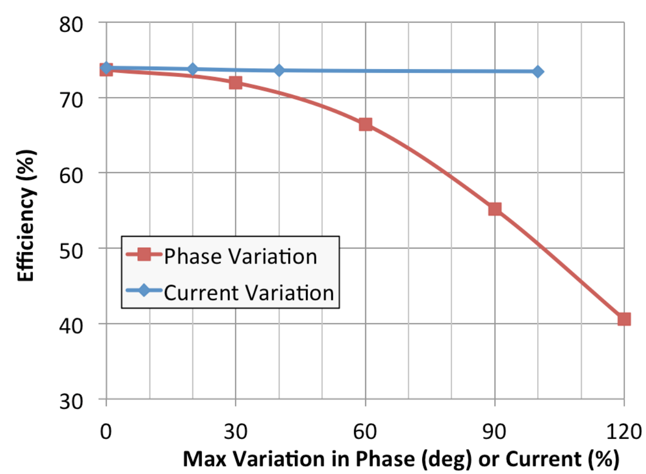
Predicted performances from simulations







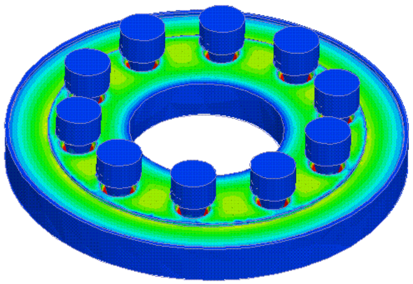
- Modeling approach is to add phase and current variations between successive bunches in MAGIC-2D
- Efficiency is not sensitive to current variation
- Efficiency is not sensitive to phase variation up to 30°



Courtesy of Thales and CPI

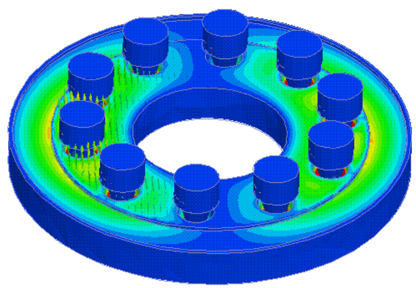
Thales/CPI MBIOT

- Many modes can be excited in the output cavity
- Modes closest to fundamental and harmonic frequencies are of concern
- Risks of exciting these modes are considered low due to: 1) low phase variance between beams 2) high Q modes 3) Δf of modes

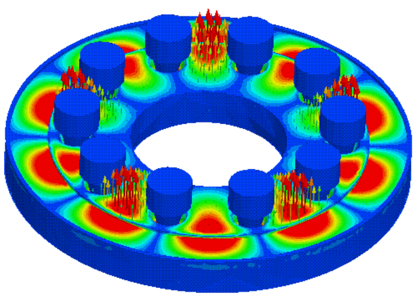


Operating mode (TM010)

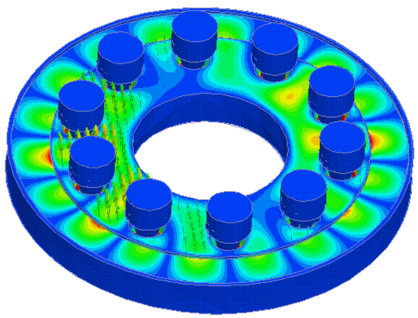
f = 704 MHz



f = 740 MHz



f = 1499 MHz



f = 2154 MHz

Courtesy of Thales and CPI

- MBIOT is now being built and procurement of main components is underway: Gun and Input Circuit (with HV enclosure) will be done by Thales, and CPI will build tube and cart
- Exhaust in June 2016
- First tests at CPI in July 2016
- Delivery to Cern in August 2016 and final test at Cern in September 2016

Summary

- Toshiba klystron prototype successfully tested and delivered to Lund
- Thales klystron prototype built
- CPI klystron prototype being manufactured
- L-3 MBIOT has been built and currently being tested at factory
- Thales/CPI IOT design finished; manufacturing ongoing

Thank you!

And thanks to:

- Toshiba Electron Devices
- Thales Electron Devices
- CPI
- L-3

And the ESS RF group