TESTING OF THE ESS MB-IOT PROTOTYPES

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IPAC 2018

- Introduction to ESS
- Design
- Test Results
- Energy Considerations
- Conclusion

Introduction

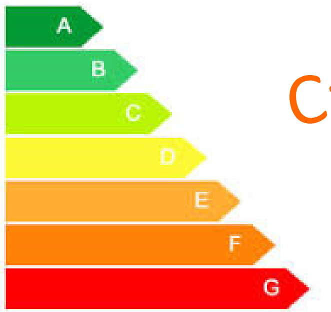
The European Spallation Source is under construction in the city of Lund, in southern Sweden.
ESS will offer neutron beams of unparalleled brightness for cold neutrons, delivering more neutrons than the world's most powerful reactor-based neutron sources today, and with higher peak intensity than any other spallation source.

Key parameters:

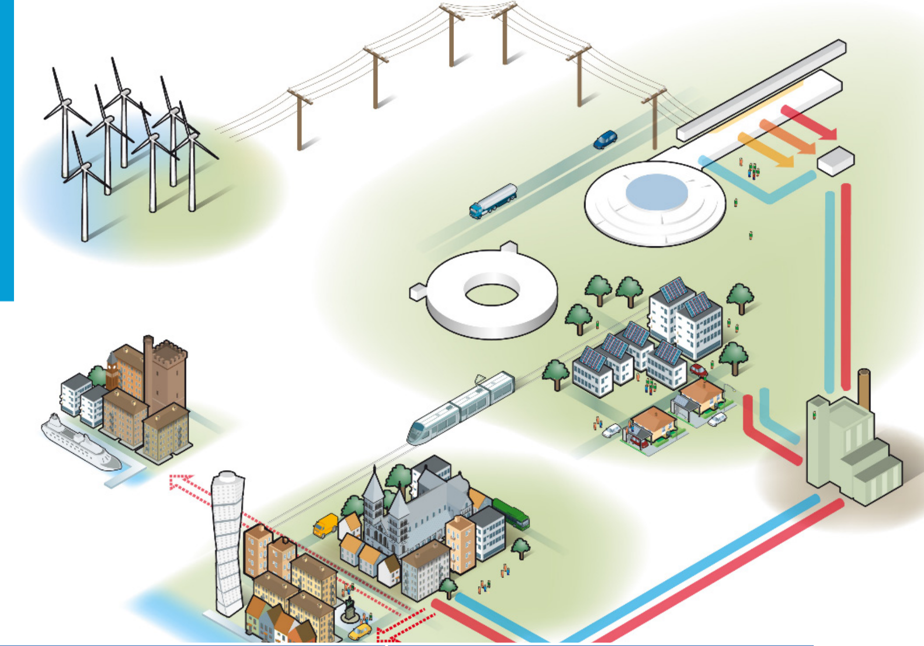
- 2.86 ms pulses
- 14 Hz
- 2 GeV
- 62.5 mA peak
- 5 MW average beam power
- Peak beam power 125 MW

The ESS Requirement

Slide from 2014



Carbon Neutral
Innovative
Green

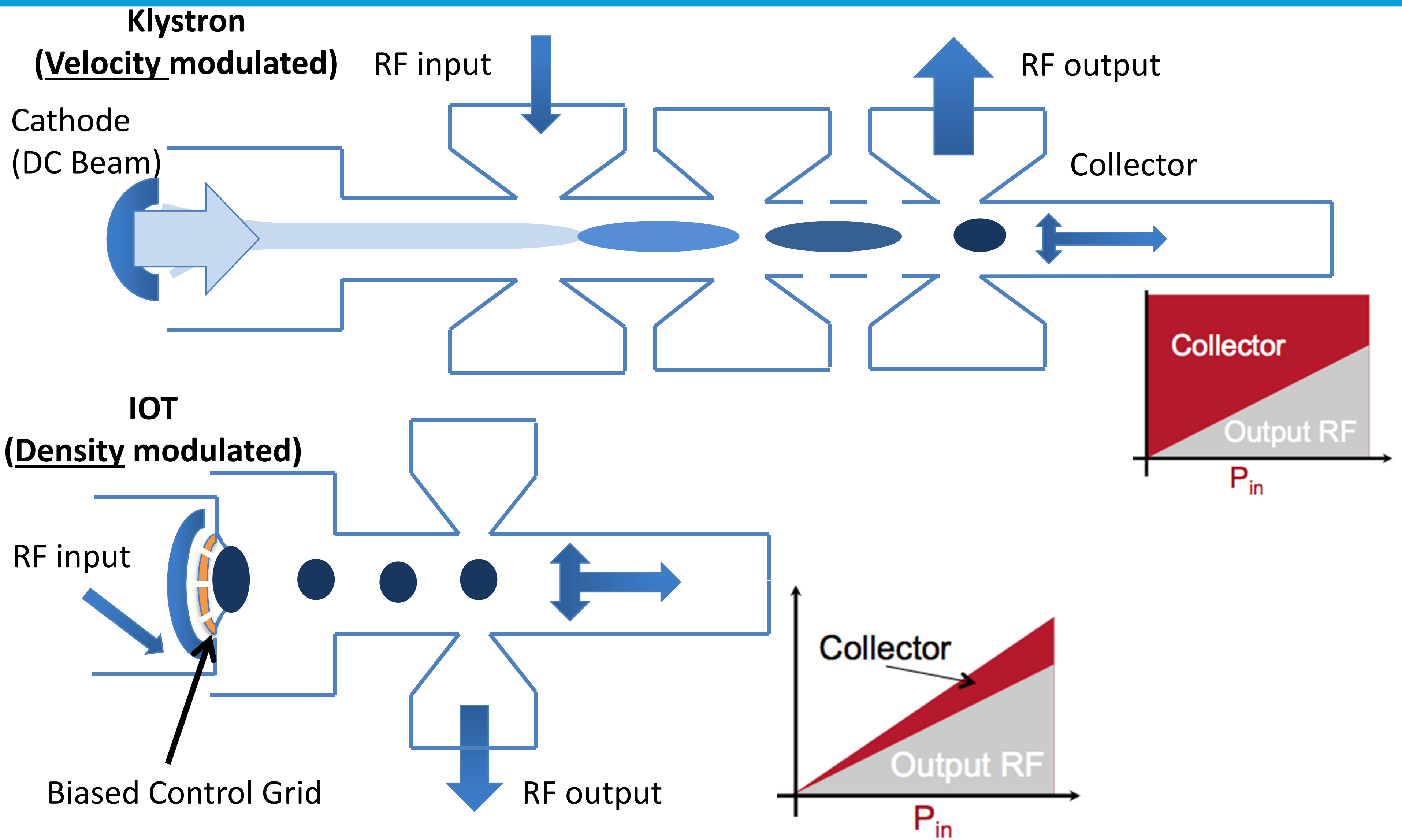


Accelerating Structure	Freq. (MHz)	Quantity	Max Beam Power (kW)
RFQ, DTL	352	6	2200**
Spoke	352	26	330**
Elliptical Medium Beta	704	36	860**
Elliptical High Beta	704	44+40	1100**

Opportunity to develop Super Power IOT

** Plus overhead for control

IOT Efficiency and Principle



The Performance Comparison

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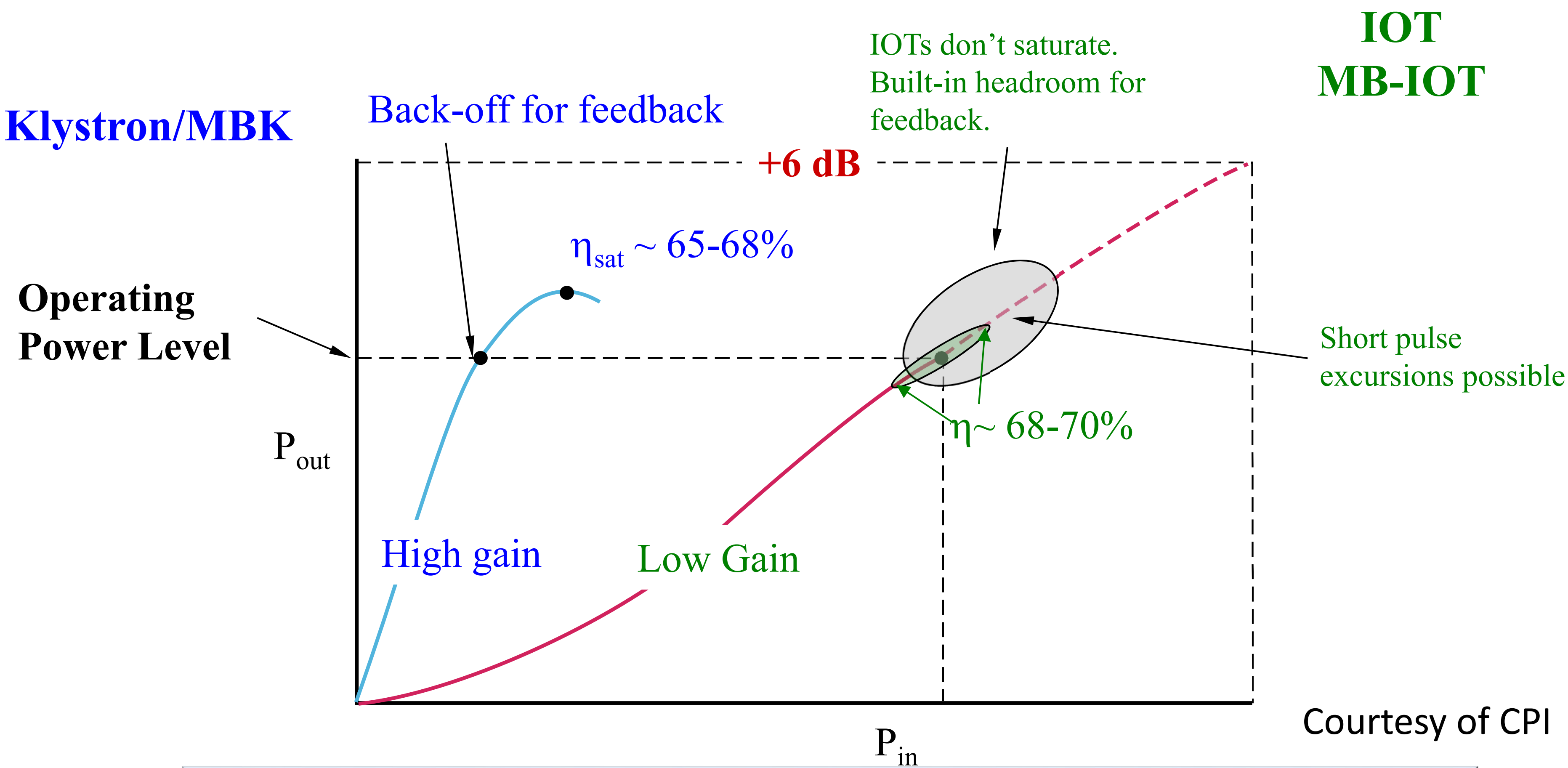

Courtesy of CPI

Klystrons: Back-off for feedback cost 20-30% in efficiency

IOTs: Operate close to max efficiency

Key advantages of IOTs

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- ✓ High efficiency even when operating 'backed-off' for reduced RF output or regulation
- ✓ Good linearity
- ✓ Can be small and compact
- ✓ Power is pulsed by RF instead of HV
- ✓ Lower operating voltage
- X Lower gain
- X More complicated in case of multi-beam design

Particularly beneficial for machines with:

- Varying power loads
- Non uniform power profiles
- Margins for overhead for regulation
- One-to-one relationship with amplifier to accelerating structure
- Common high voltage supply to multiple RF sources
- High average power applications

Accelerators currently using IOTs

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Diamond Light Source

- **Existing tubes limited to approx. 80 kW CW, 130 kW long pulse operation**
- **Higher power requirement achieved by combination of IOT outputs**
- **A MW IOT would require a multi-beam approach**

Elettra

Metrology Light Source (Willy Wien Laboratory)

NSLS II

ALBA

CERN

An IOT for ESS

ESS placed contracts for two **Technology Demonstrators**

- *L3 Electron Devices*
- Consortium of *Thales Electron Devices (TED)* and *Communications and Power Industries (CPI)*

Key Parameters	Specification
Frequency	**704.42 MHz**
Maximum Power	**1.2 MW**
RF Pulse length	Up to 3.5 ms (@ 14 Hz)
Duty factor	Up to 5%
Efficiency	Target > 65%
High Voltage	< 50 kV
Design Lifetime	> 50,000 hrs

- CERN to set up a test stand and carry out site testing

The ESS MB-IOTs

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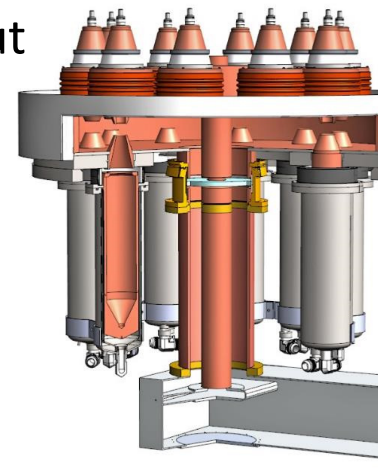
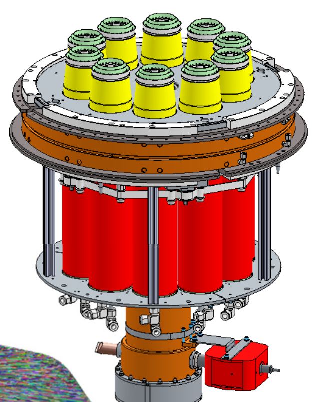
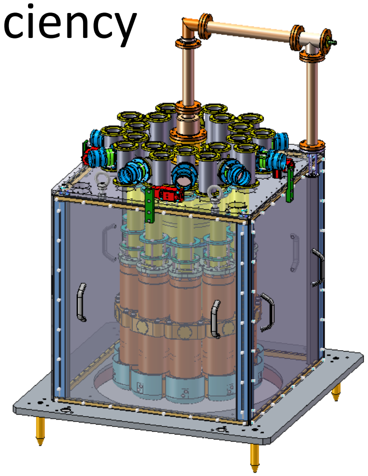
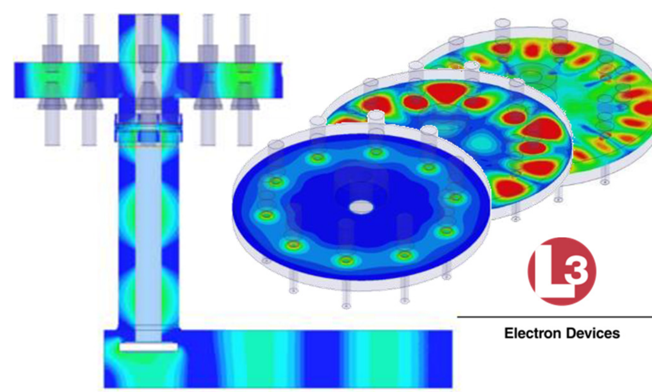
- 10 Electron guns placed in a circle
- Cavity with 10 separate interaction gaps and single output
- Magnetic focusing (Permanent magnet or solenoid)
- Output windows based on high power klystron designs
- Suppliers carried out extensive modelling and simulation (beam optics, mode analysis, thermal and structural analysis, innovative manufacturing, …)
- Manufacturing validation through single beam prototyping and sub-assembly test vehicles, …
- Design driven by reliability and efficiency



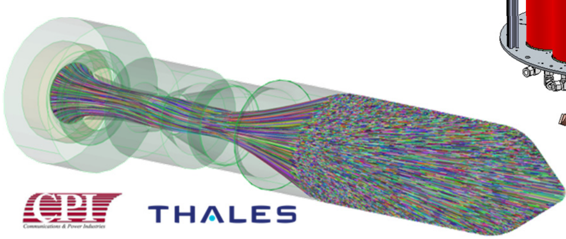
L3 Electron Devices







L3 Electron Devices

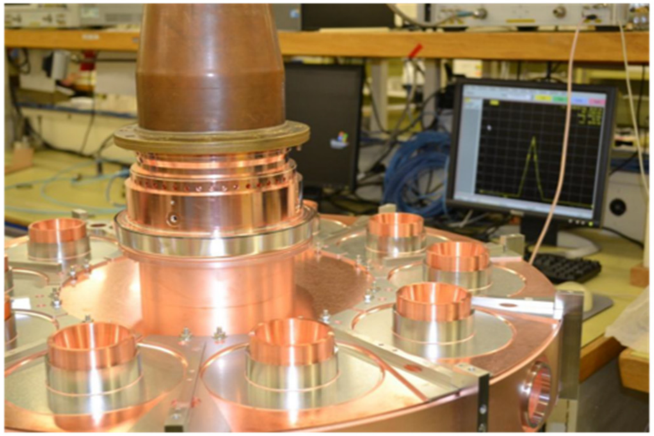


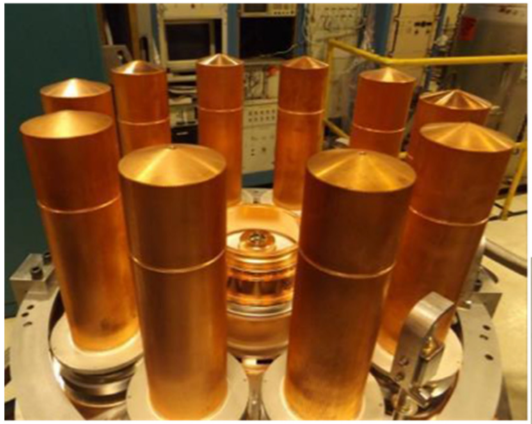
CPI THALES

CPI THALES

From Simulation to Reality: L3

EUROPEAN SPALLATION SOURCE

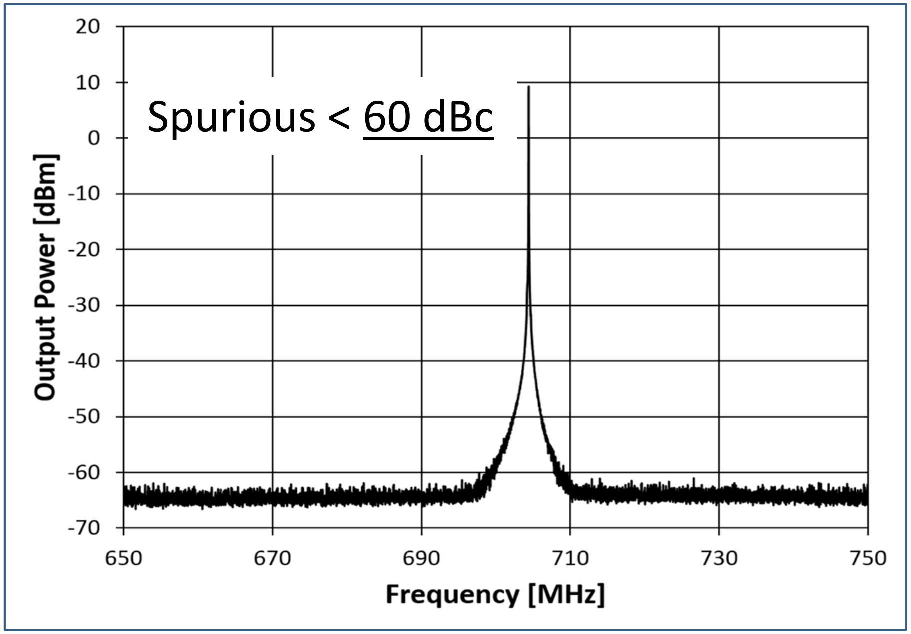




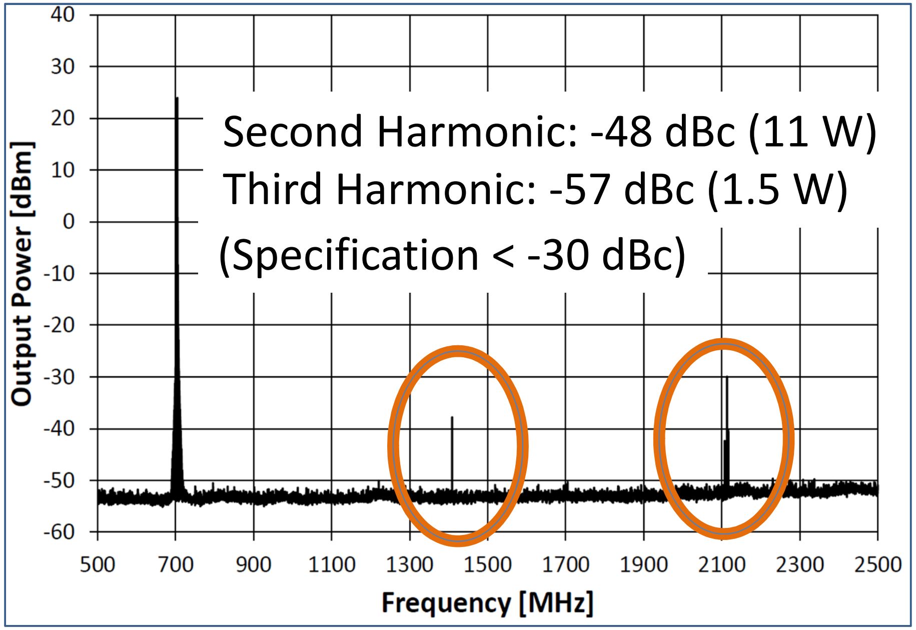
Electron Devices

L3 IOT Factory Acceptance Results

Output spectrum at 1 MW



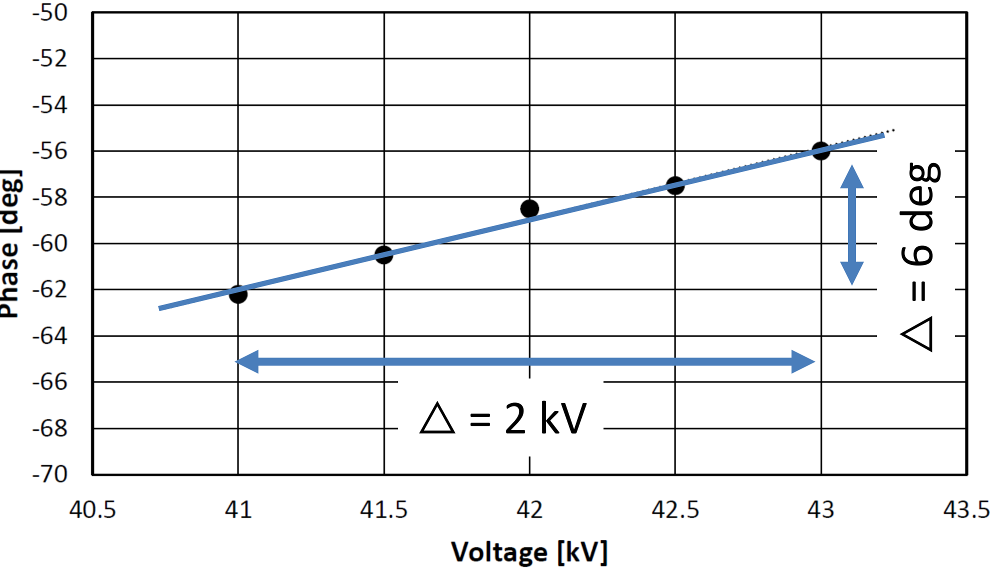
Harmonic content at 1 MW



(Coupling factors calibrated at harmonics)

No power seen from harmonic cavity modes and no sign of instability

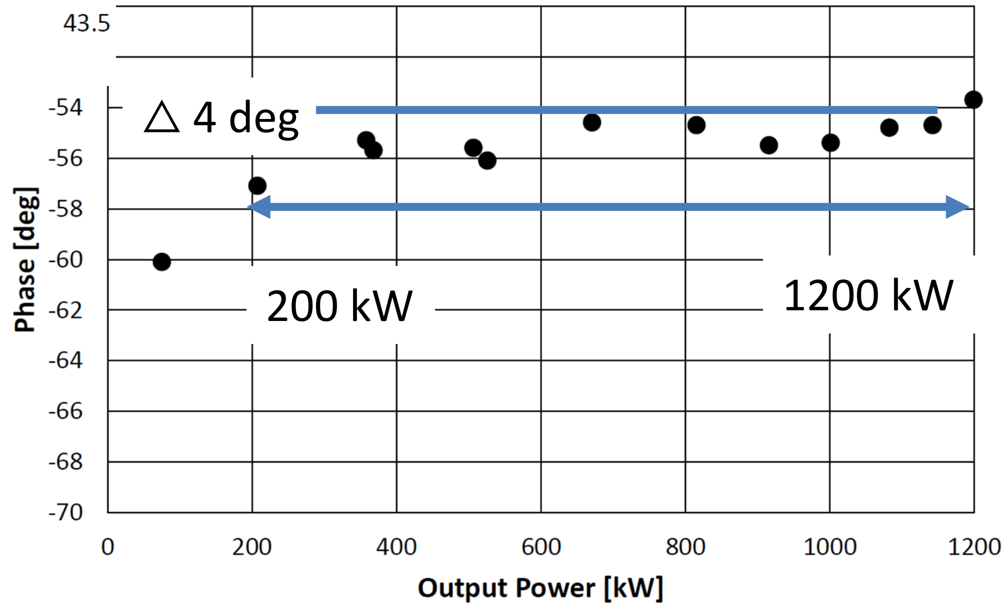
L3 IOT Factory Acceptance Results



- **Low Insertion Phase: 3 deg / kV**
- **Linear and reduces phase variation due to HV ripple**

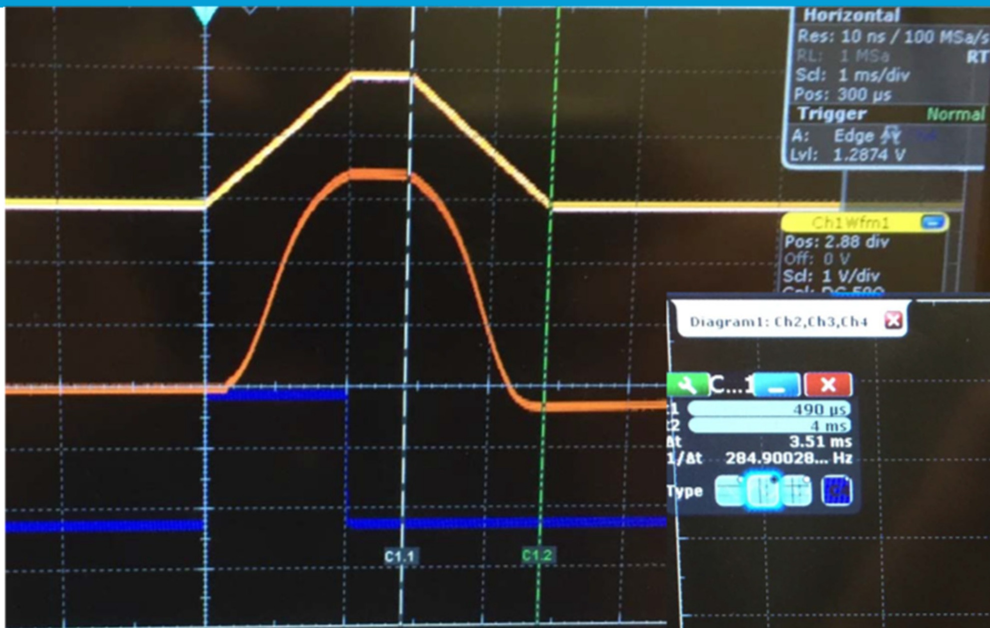
  Data taken by varying beam voltage at constant output power (1 MW)

- **Monotonic phase shift for increasing output power**
- **Total phase shift < 4 deg from 20% to 100% of nominal output**
- **Measured at constant beam voltage**



L3 IOT Results

EUROPEAN SPALLATION SOURCE

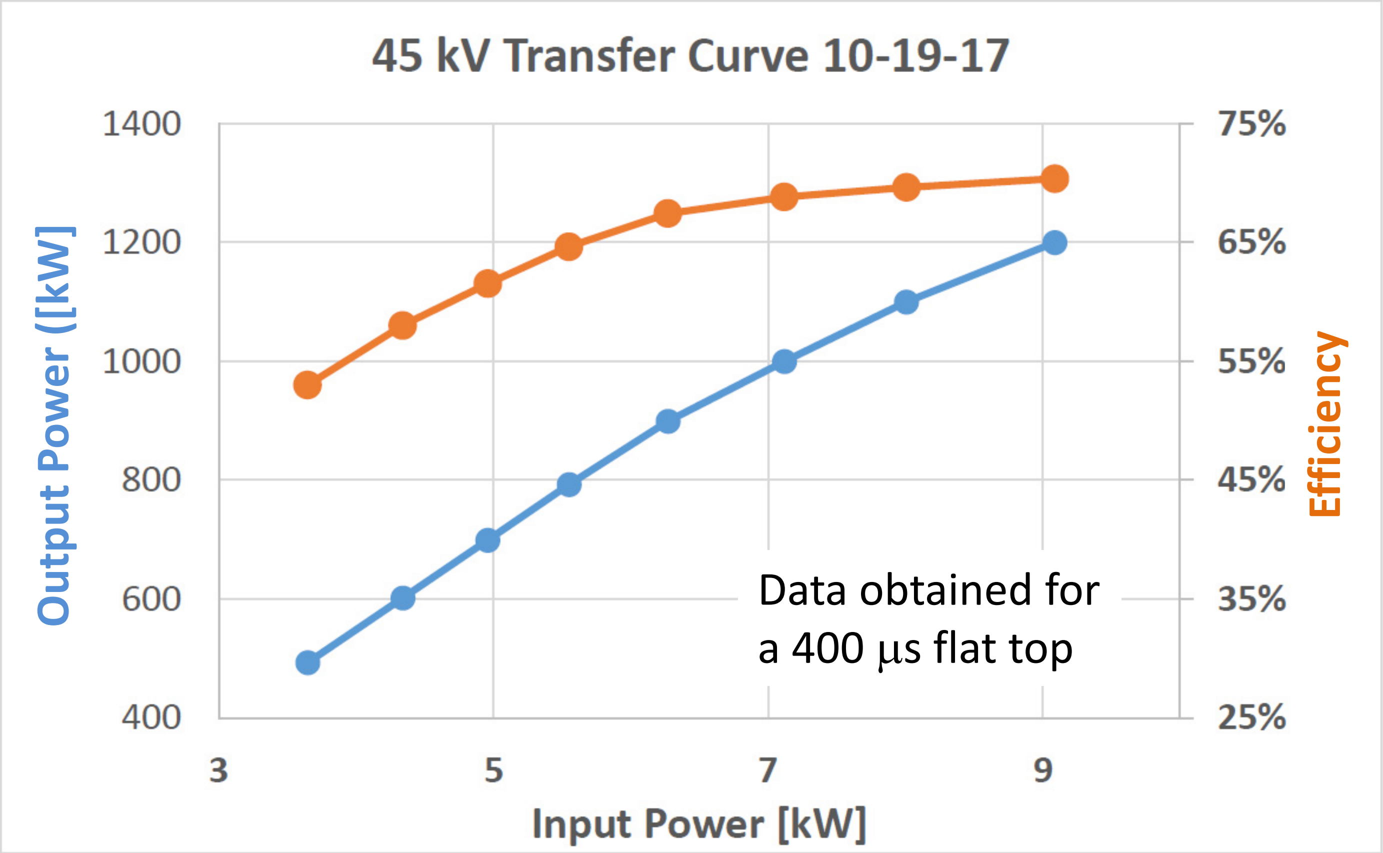


Scope capture with 400 µs flat top
Input Drive: Yellow trace
RF Output Power: Orange trace

1.2 MW output, 3.5 ms flat top
Rep. Rate = 14 Hz
Cathode current: Green trace
RF Output Power: Orange trace

Testing carried out at CERN

L3 IOT Results



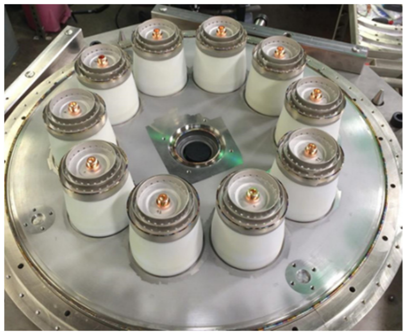
Long pulse operation:

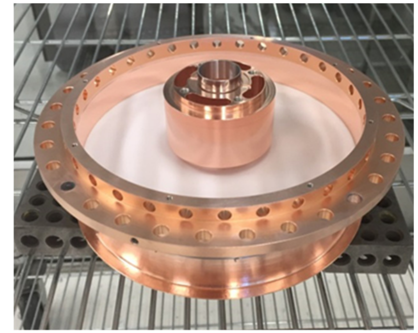
1.2 MW achieved with 3.5 ms flat top with 1 ms ramps on leading and training edges

1.14 MW achieved at 4 ms flat top, limited by the drivers

From Simulation to Reality: Thales and CPI

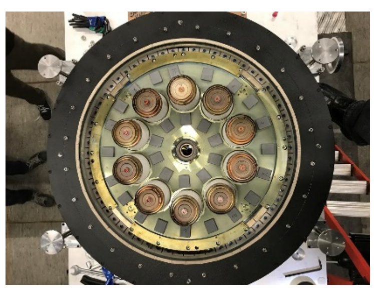
EUROPEAN SPALLATION SOURCE

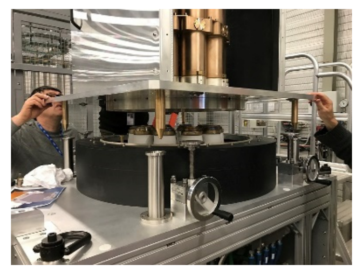


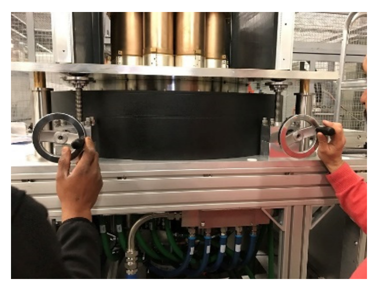


CPI
Communications & Power Industries

THALES

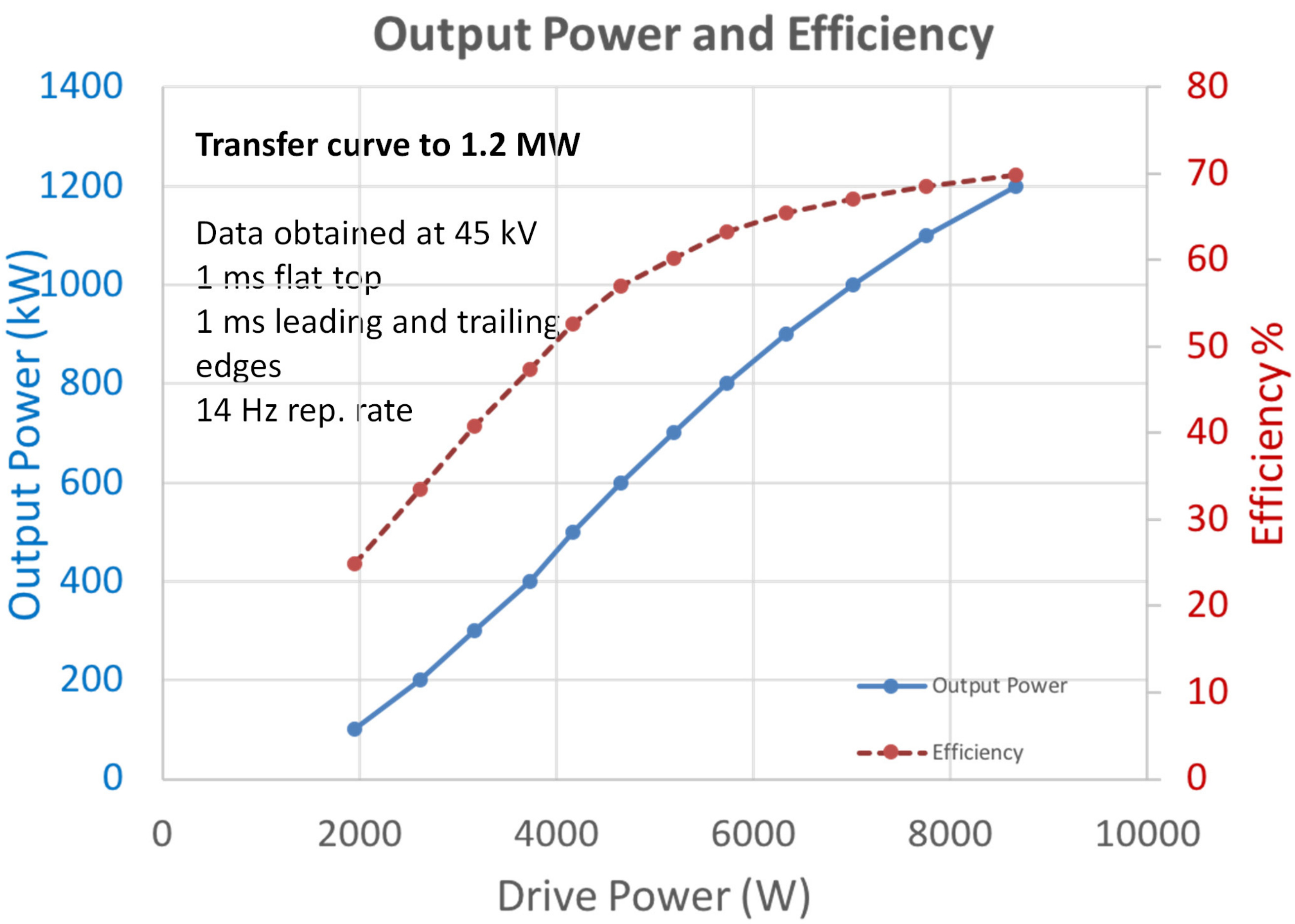


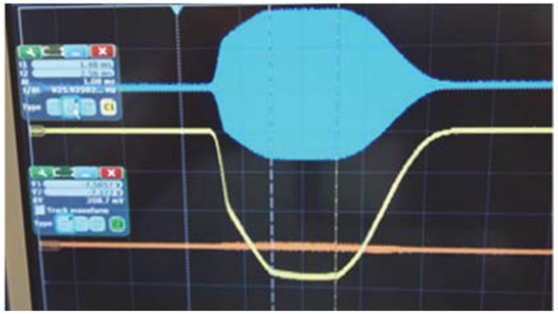




Assembly at CERN

TED/CPI IOT Results

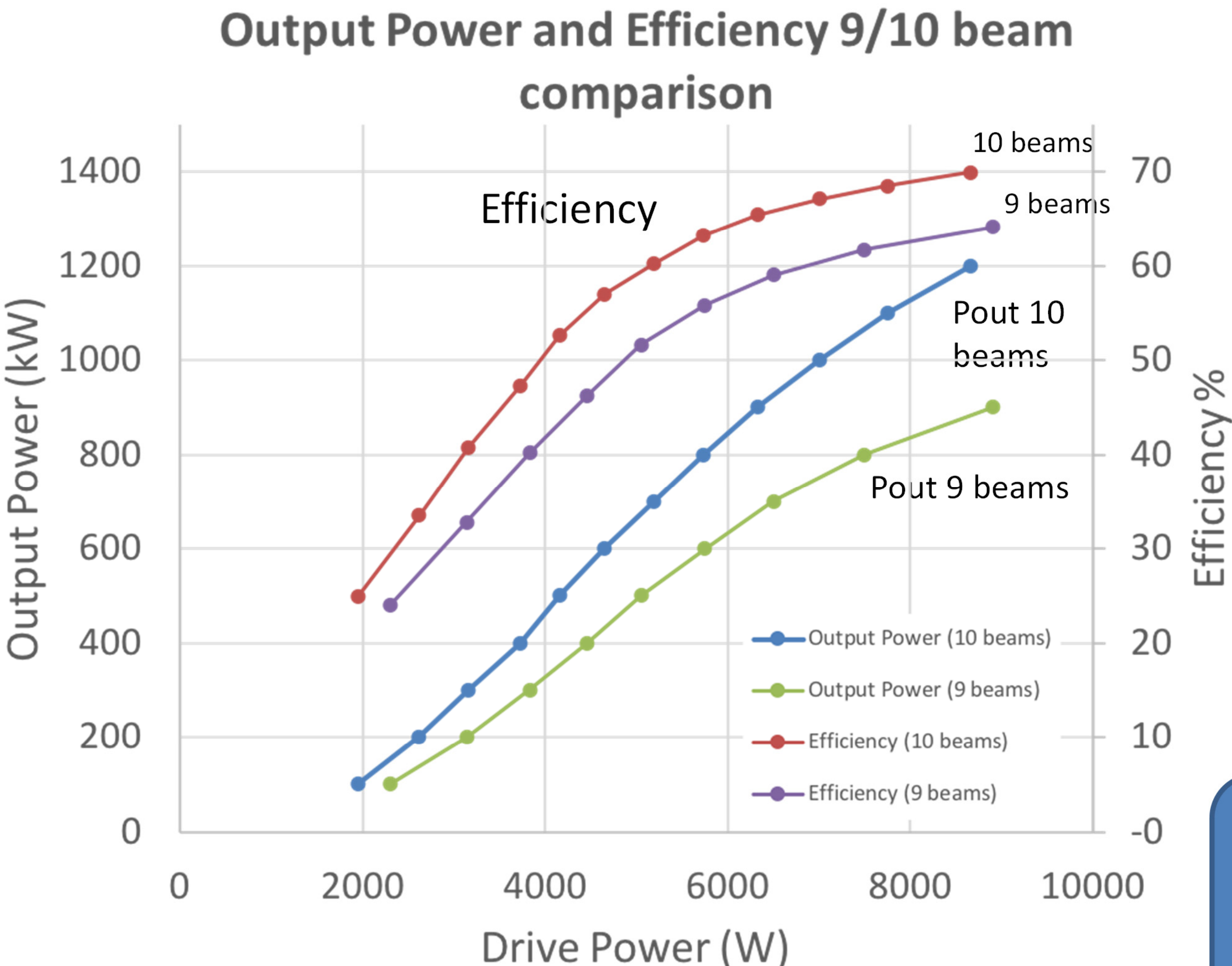




Yellow: Total Collector current
Blue: RF output pulse

IOT installed at CERN

TED/CPI IOT Results



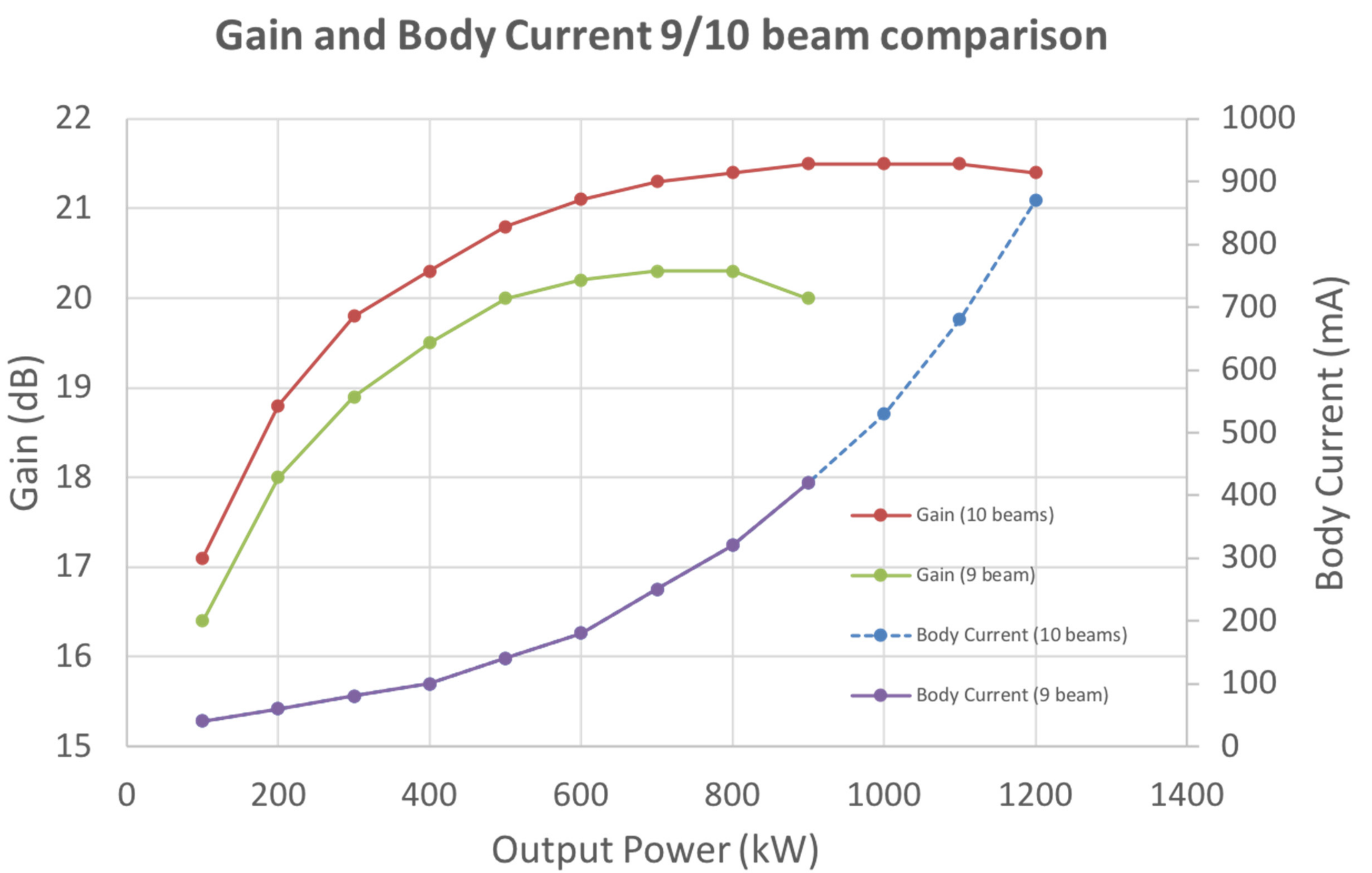
One gun off
Input cavity removed.

No signs of instability

Drive limited due to missing module

Pushing a single gun to higher current, equivalent to 1.4 MW, showed no sign of saturation

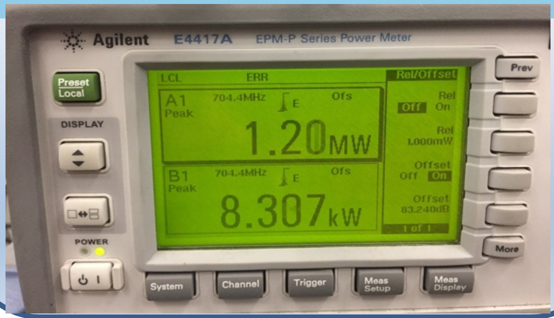
TED/CPI IOT Results

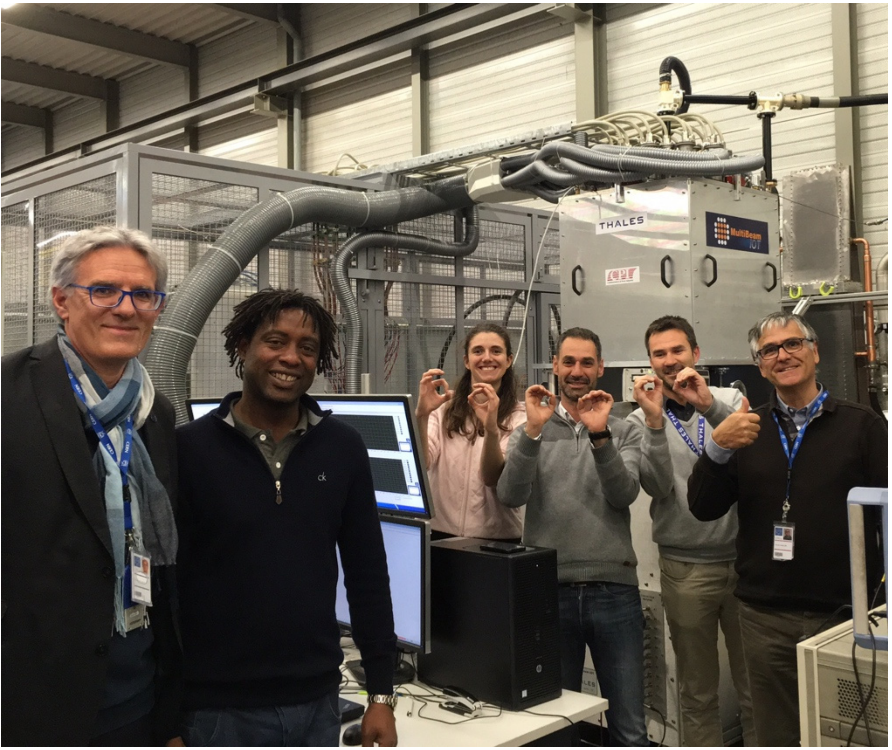


MBIOT Status

MBIOTs delivered to CERN for testing
Both MBIOTs have delivered 1.2 MW
Overall Technical Specification achieved

World Record





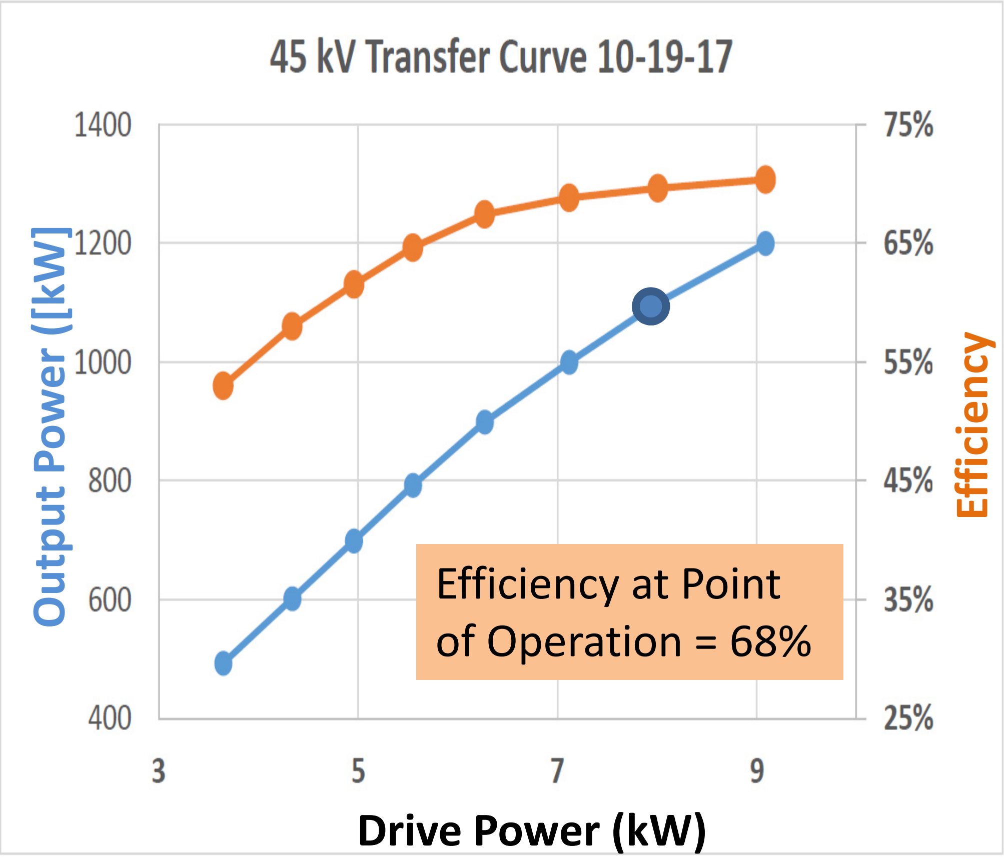
Thales/CPI MBIOT

L3 MBIOT

Testing at CERN

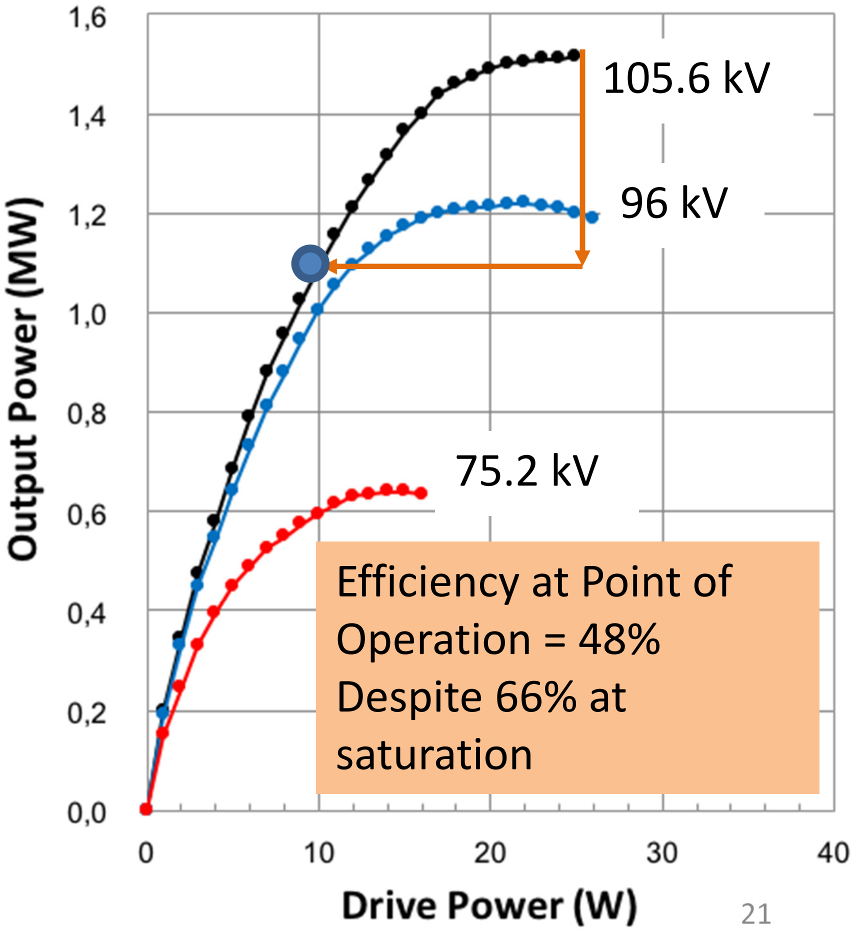
The efficiency promise of IOTs for operation below 'Saturation'

L3 MBIOT



For Power to Beam of 1.1 MW
Operation with 20% Overhead for regulation

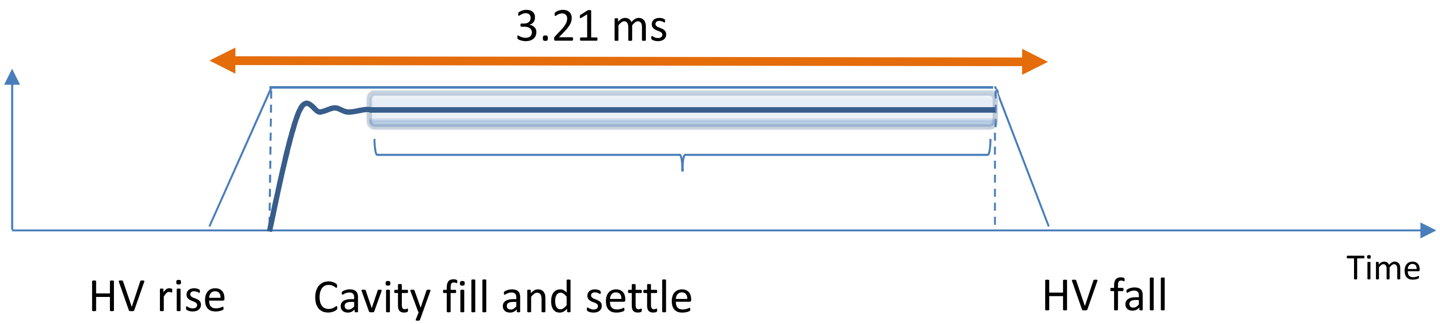
Prototype Klystron Transfer Curve



Energy and Power Estimates of Klystrons vs IOTs

Key Numbers used in Calculations

Operating hours per year	5000 hrs
Average Power to the beam for all HB	1060 kW_{peak}
Pulse width and repetition rate	3.21 ms / 14 Hz
Power overhead for regulation	20%
IOT efficiency at point of operation	68.9%
Klystron efficiency at saturation	66%
Klystron modulator / IOT power supply efficiency	92% / 95%
Klystron / IOT auxiliary power	3.7 kW / 5 kW

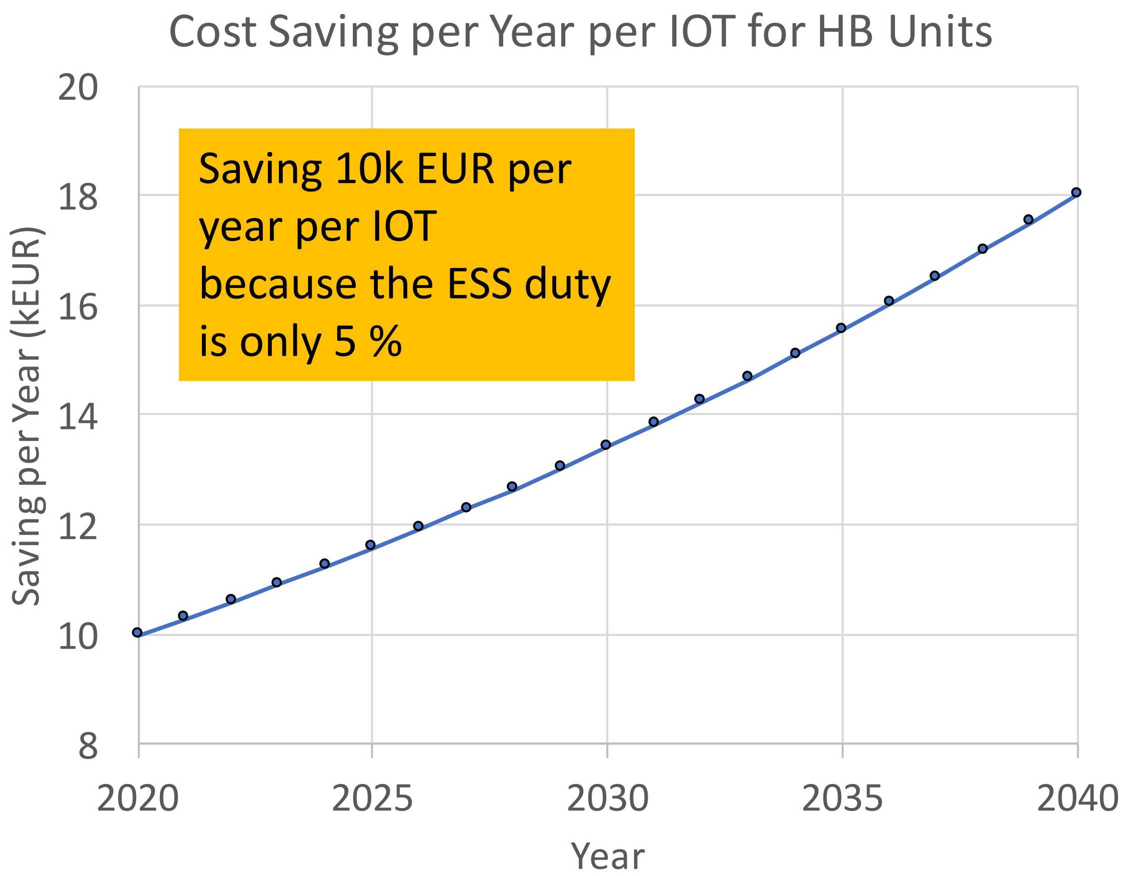


Efficiency and Cost

Power Consumption

High Beta Linac	Klystrons	IOTs	Energy Saving of using IOTs
Phase 1: **44 Amplifiers**	26.5 GWh / Year	19.0 GWh / Year	7.5 GWh / Year
Phase 2: **84 Amplifiers**	50.7 GWh / Year	36.2 GWh / Year	14.5 GWh / Year
Split technology from year 2025 **- 44 Klystrons** **- 40 IOTs**	26.5 GWh / Year	17.2 GWh / Year	7 GWh / Year

Calculated Cost Saving per IOT for ESS



Based on contracts for klystrons for medium beta and budgetary estimates for initial series IOTs the financial payback time is 10 years

Note
ESS duty is only 5 % and higher duty machine would see much shorter payback time

Conclusion

- ESS, together with industry, delivered two successful technology demonstrators
- The efficiency of IOTs is superior to klystrons for high power machines particularly for machines with high power overhead requirements
- Further development, pre-series production, will reduce risk and cost
- Budget, schedule and risk constraints at ESS means that ESS must opt for klystrons for the first part of the high beta linac
- ESS will continue to follow the development and hope that new high power accelerators will be able to benefit from the investment
- The MB-IOTs developed for ESS have been constructed using CW capable components. High power CW operation could result in a payback time of 1 – 2 years through savings in electrical cost

The MB-IOT technology is available – Use it!