IOTs at ESS

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European Spallation Source ERIC
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Disclaimer 1: not much has happened on MBIOTs after 2019!

This talk will be a recap of the MBIOT history

Disclaimer 2: Most of the material comes from M. Jensen, who could not attend the workshop

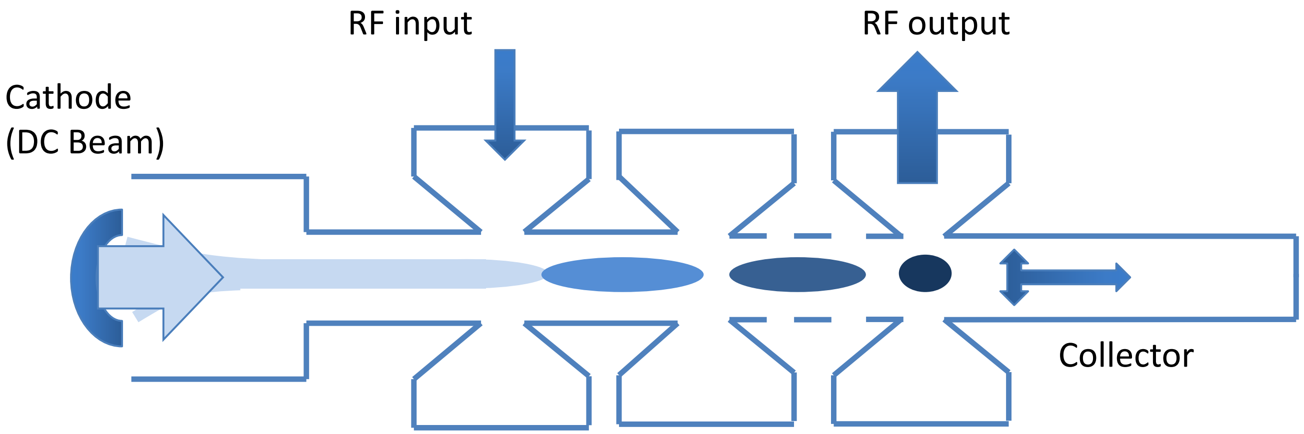
Outline

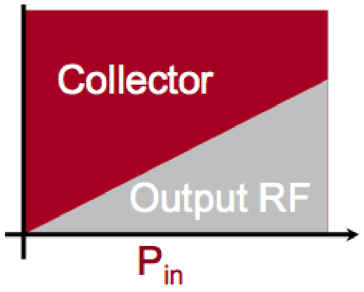
- IOT basics and working principles
- IOTs as high efficiency power sources
- IOT advantages and limitations
- Multi Beam IOT for ESS: development and results
- Conclusion and future perspectives

Working principles

Klystron
(<u>Velocity</u> modulated): class A

Full DC input also with zero drive
(and zero output)



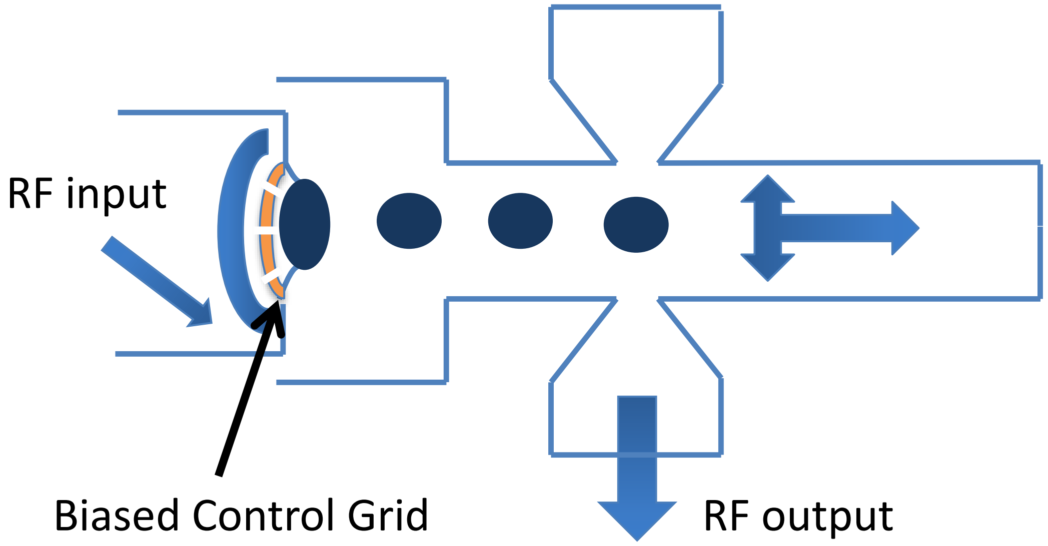


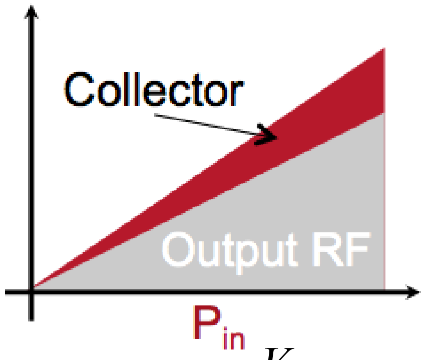
$$I_0 = P(V_0)^{3/2}$$

$$\eta = \frac{P_{out}}{P_0} = \frac{P_{out}}{I_0 V_0}$$

IOT
(<u>Density</u> modulated): class B

No collector dissipation with zero
drive





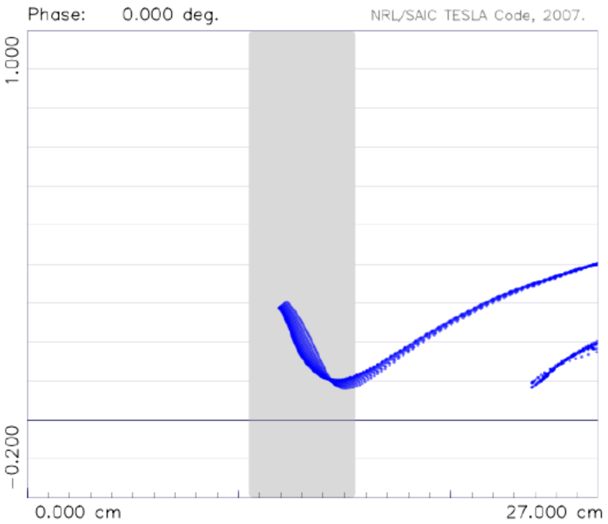
$$I = P(V_g + \frac{V_0}{m})^{3/2}$$

IOT as high efficiency power source

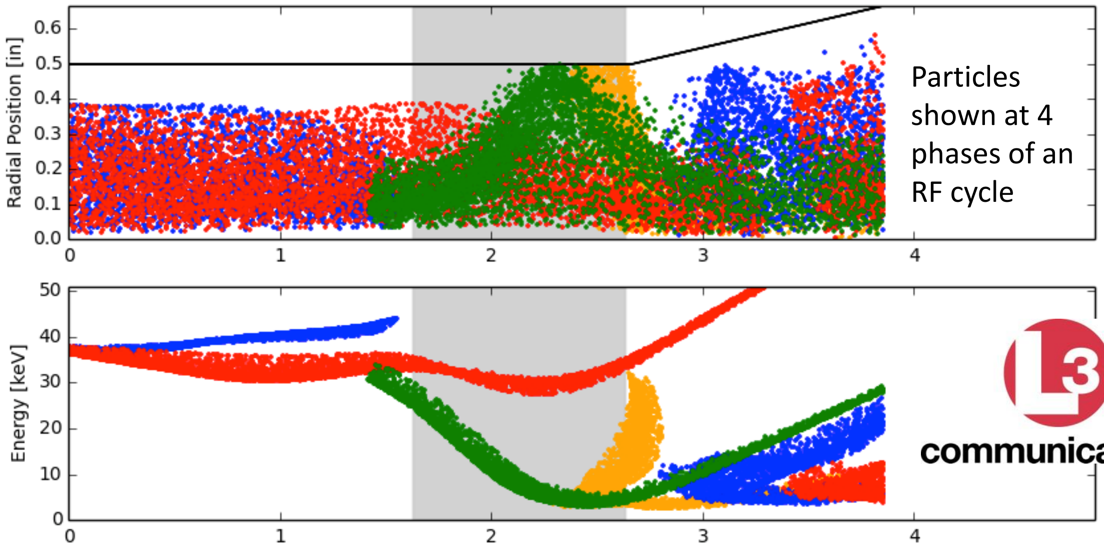
- Beam comes out of the cathode-grid already bunched ✓
- Bunch saturation is 100% ✓
- There is no velocity modulation, so energy spread in the beam is very low. ✗

No velocity modulation would be good…..if we had infinitely short bunches and no space charge. But in reality we know that we need the bunch to be congregated to achieve the maximum extraction efficiency.

Extraction efficiency is tipically around 70-75%
BUT…….



L. Ives, Cal. Creek Research, “Development of a 402.5 MHz 140 kW IOT”



communications

IOT Operational efficiency

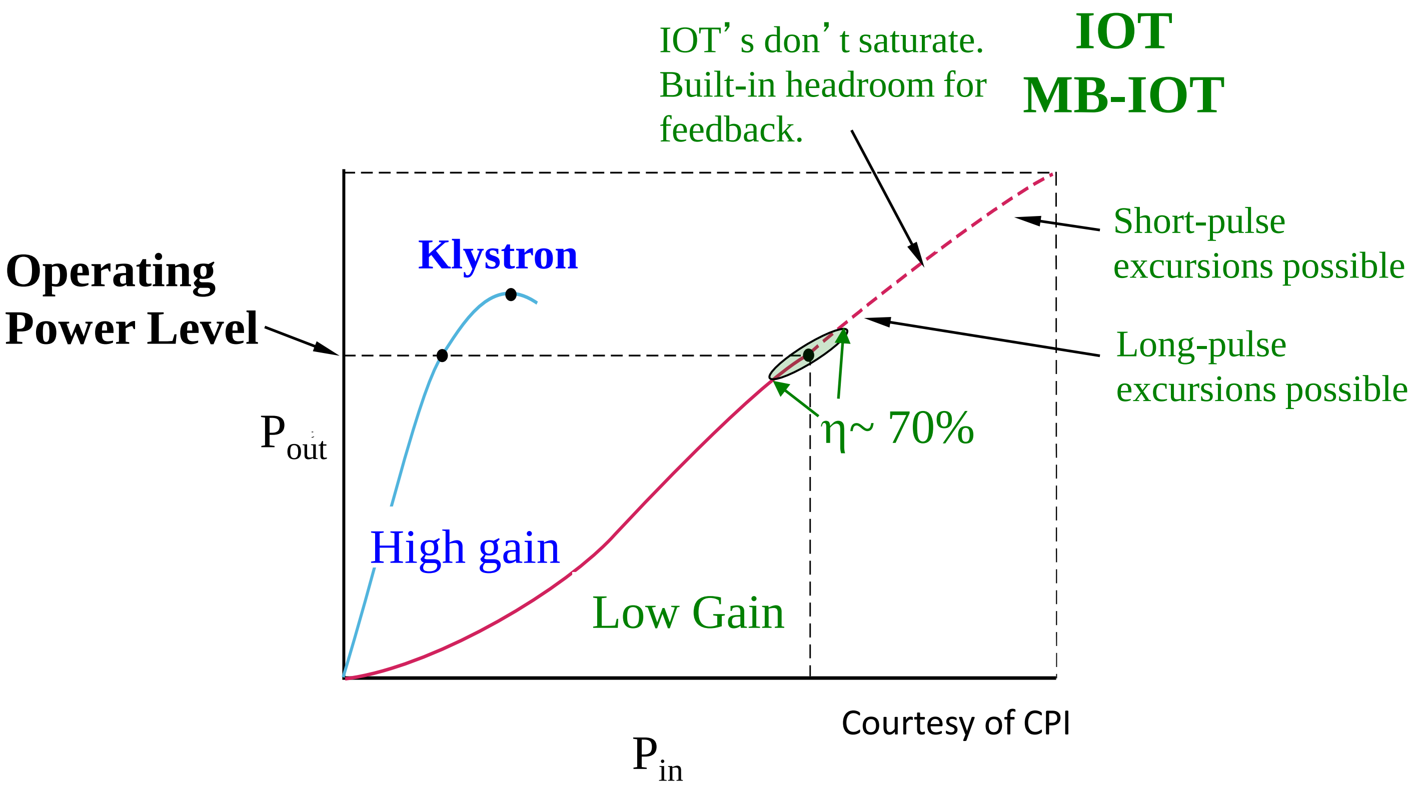
We have to consider **OPERATIONAL efficiency**!

The current also depends on the grid voltage.

$$I = P(V_g + \frac{V_0}{m})^{3/2}$$

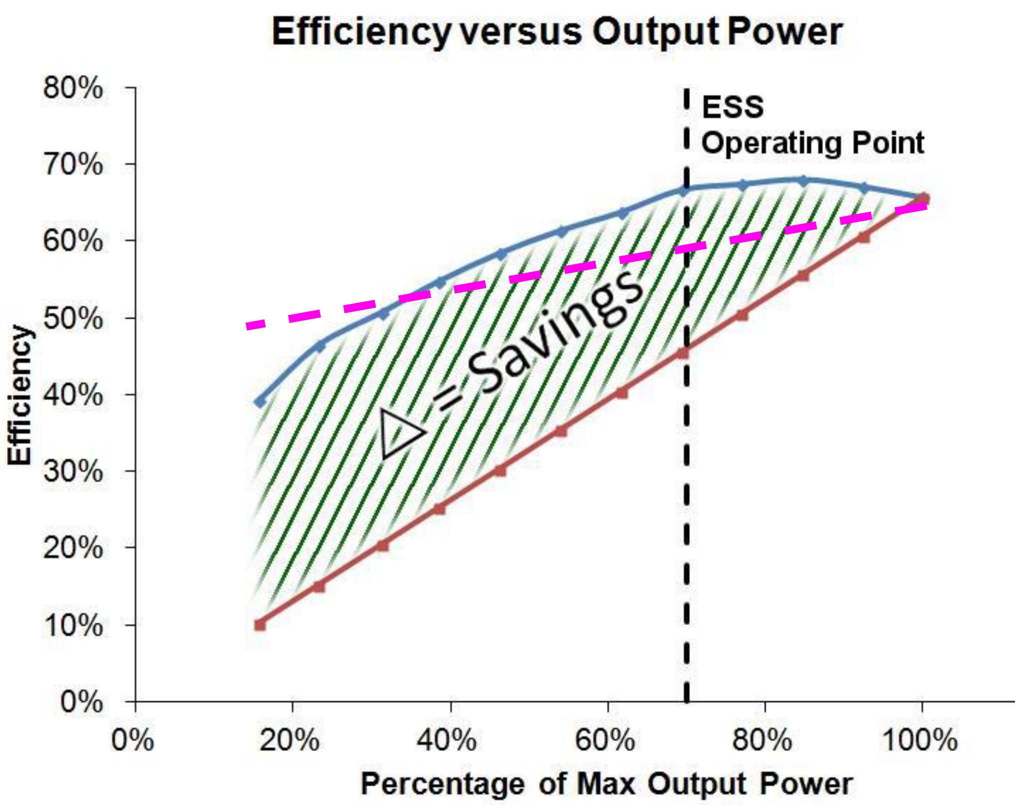
As a result, the tube does not saturate as fast as a klystron

- ✓ Efficiency at point of operation (linear region) can be as high as 70%
- ✓ Efficiency drops slowly at reduced output power
- ✓ Good Linearity



Courtesy of CPI

Operational efficiency IOT vs klystron



Good for machines which require the amplifier to operate

- At different power levels
- With varying power loads
- With Non uniform power profiles
- With Margins for overhead for regulation
- One-to-one relationship with amplifier to accelerating structure
- Common HV supply to multiple power sources

IOT measurements courtesy of M. Boyle, L3

- Based on broadcast IOT L-4444
- System setup limited by drive power and beam voltage
- IOT setup for maximum gain (not efficiency) without breakdown

- Klystron assumed to have same saturated efficiency as the IOT
- No optimisation of coupling, voltages, perveance for different power levels

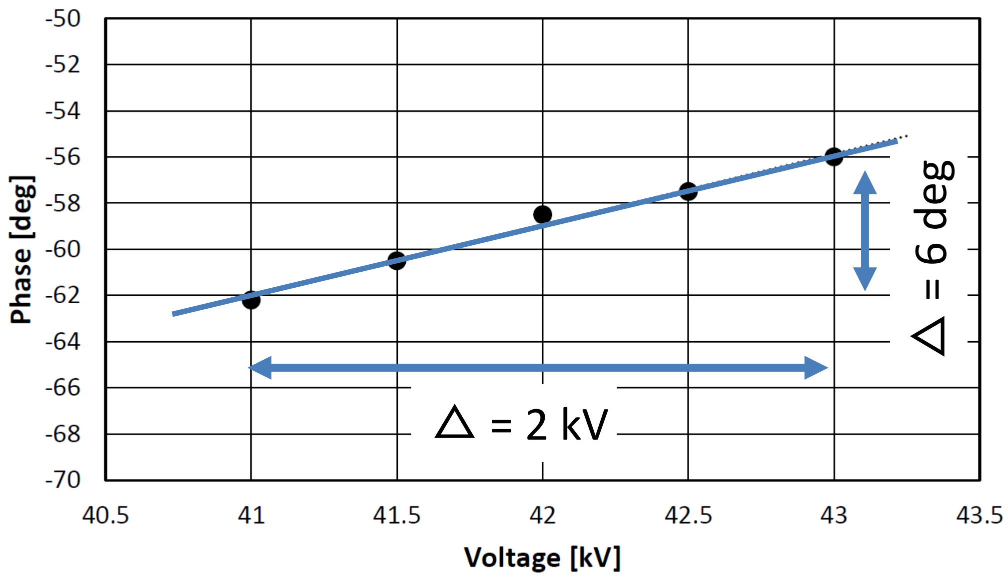
- Klystron can partially catch up when optimizing HV, output coupling and focusing -> ”static” optimization

IOT as high efficiency power source

Other advantages and drawbacks

Other advantages:

- Short, no gain cavities, so pushing factor is small
- Solenoid power is low (0-100's W)
- Small and compact
- Power is pulsed by RF instead than HV
- Collector only ever handles spent RF beam (e.g. at Eff. 50% P_{Coll} = RF power)
- Low power consumption in standby or for reduced output power



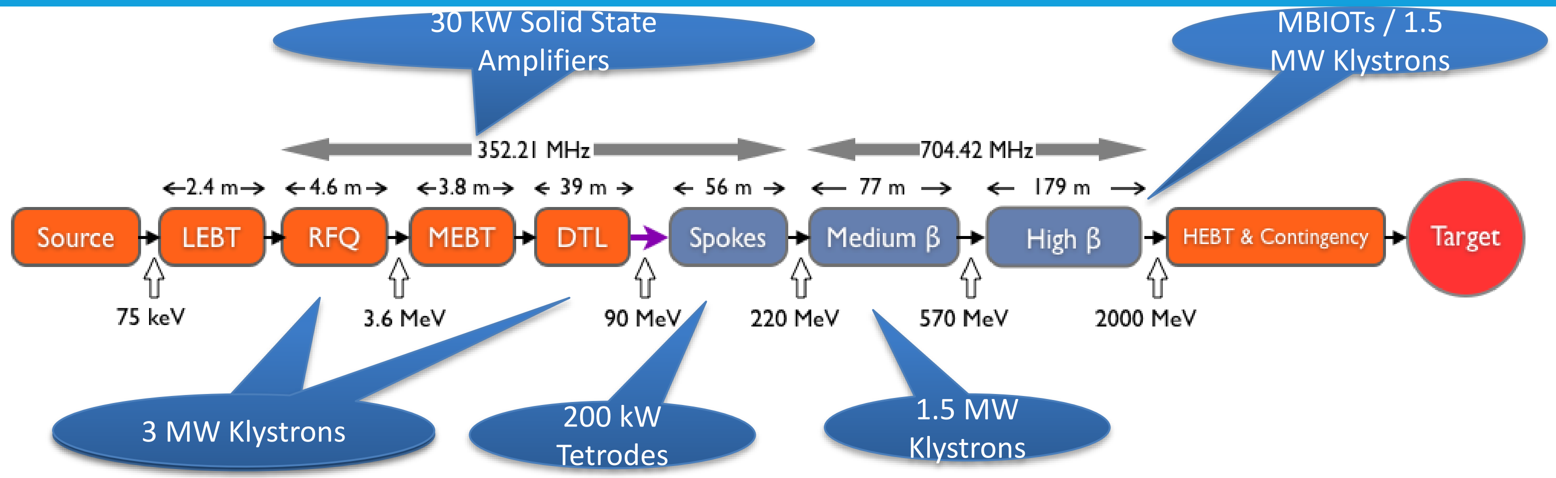
L3 MBIOT FAT: Data taken by varying beam voltage at constant output power (1 MW)

Drawbacks: Gain is low (20-23 dB). This is a smaller problem than a few years ago thanks to the improvement in solid state technology.

Frequency upper limit: about 1.3-1.5 GHz -> limit imposed by the cathode to grid distance

Multibeam design can be complicated

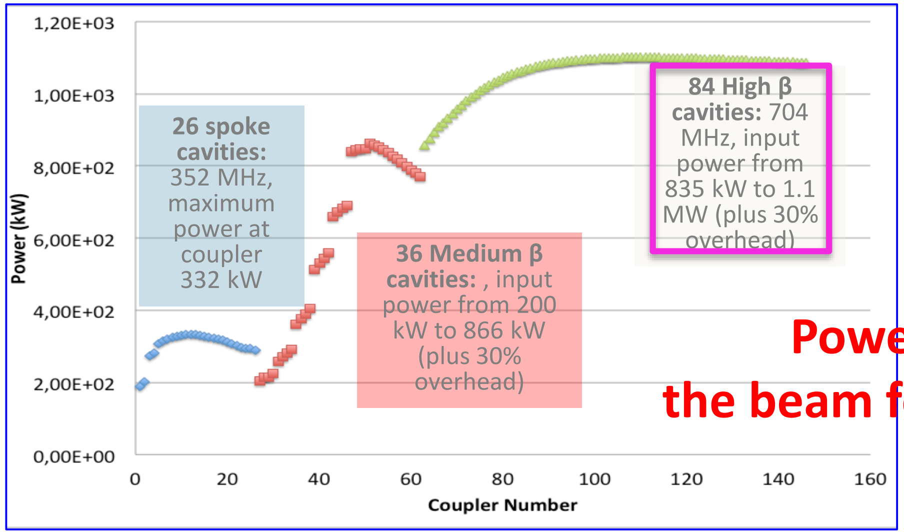
IOTs for ESS



	Frequency (MHz)	No. of Cavities	βg	Temp (°K)	RF power (kW)
Source	-	0	–	~300	–
LEBT	-	0	–	~300	–
RFQ	352.21	1	–	~300	1600**
MEBT	352.21	3	–	~300	20**
DTL	352.21	5	–	~300	2200**
Spoke	352.21	26 (2/CM)	0.5 βopt	~2	330**
Medium β	704.42	36 (4/CM)	0.67	~2	870**
High β	**704.42**	**84** (4/CM)	0.86	~2	**1100****
HEBT	–	0	–	~300	–

** Plus overhead for control

Total High Power RF: 133 MW peak (4.6% duty) plus overhead
90 MW to High Beta Section!



Power to the beam for SC linac

3.3 MW estimated power reduction by using IOTs for High Beta instead than conventional klystrons

Multi Beam IOT for ESS

How it started

2014 - ESS signed two contracts for two Technology Demonstrators:

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

Parameter	
Frequency	704.42 MHz
Output Power	≥ 1.2 MW
RF Pulse length	Up to 3.5 ms
Duty factor	Up to 5%
Efficiency	Target > 65%
Gain	≥ 20 dB
High Voltage	≤ 50 kV
Design Lifetime	> 50,000 hrs

Work carried out in collaboration with CERN

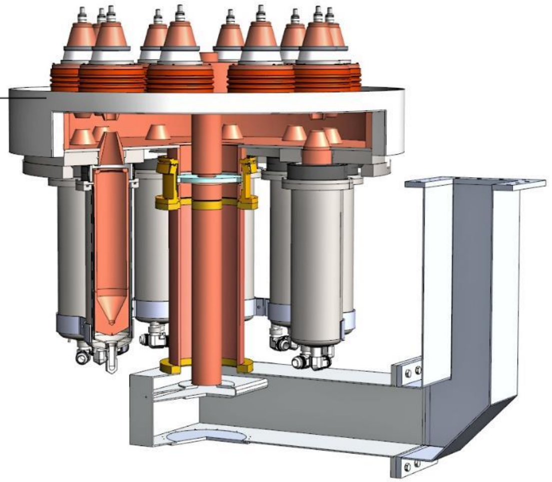
- ESS to procure prototypes
- CERN to make space and utilities available for testing

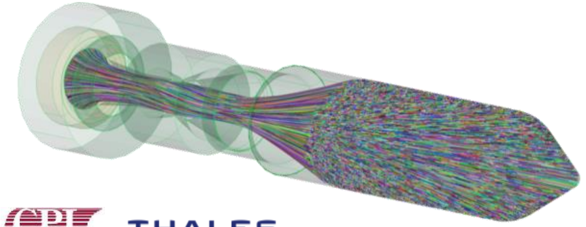
The ESS MB-IOTs

Main design features

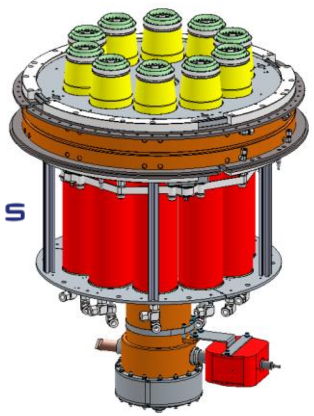
- 10 Electron guns placed in a circle
- Output cavity with 10 separate interaction gaps and single output
- Magnetic focusing (PPM or solenoid)
- Output windows based on high power klystron designs
- Individual collectors
- Extensive modeling and simulation by the suppliers (beam optics, mode analysis, thermal and structural analysis, innovative manufacturing, …)
- Manufacturing validation through single beam prototyping and sub-assembly test vehicles, …
- Design driven by reliability and efficiency

Electron Devices

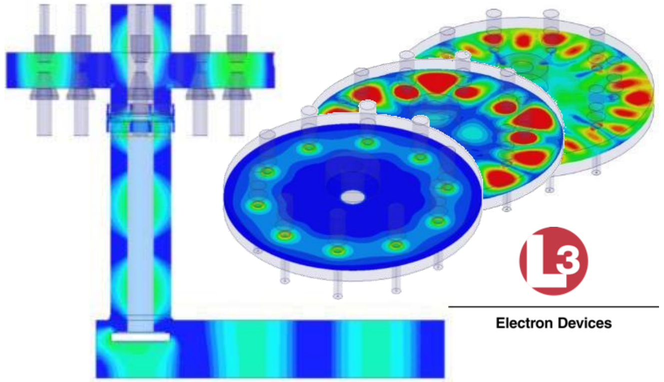




THALES



Electron Devices



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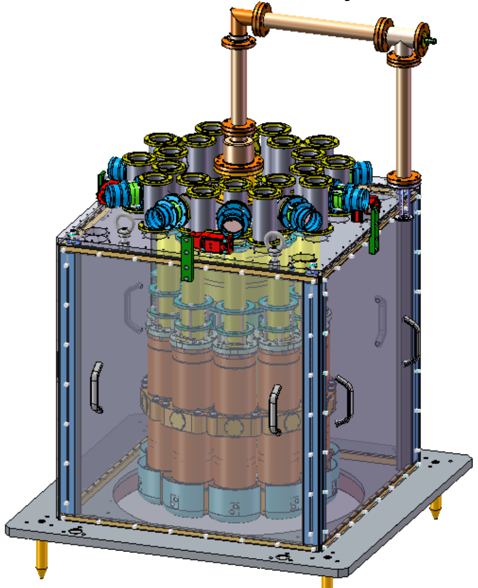
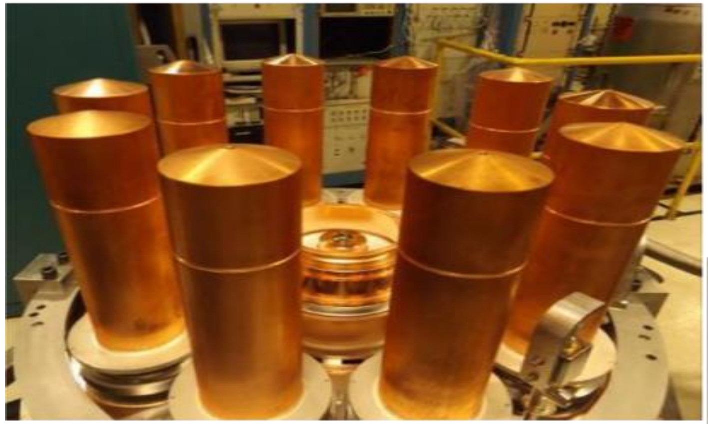


THALES

From simulations to reality: L3

EUROPEAN SPALLATION SOURCE

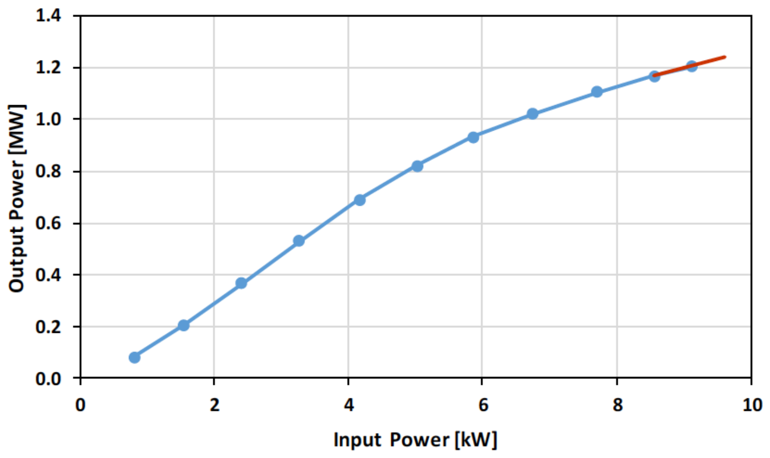


Electron Devices

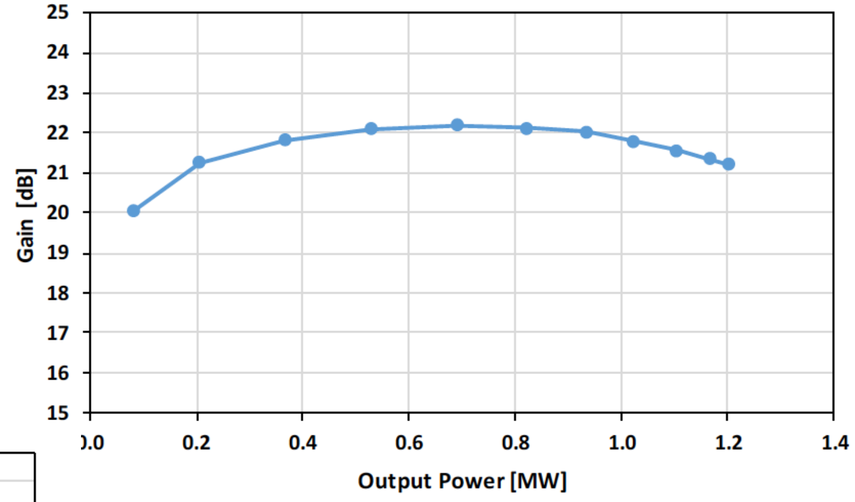
- PPM focusing
- 10 individual SS drivers (15 kW)
- Coaxial window derived from SLAC B-factory klystron
- Full RF performance with less than 10 beams

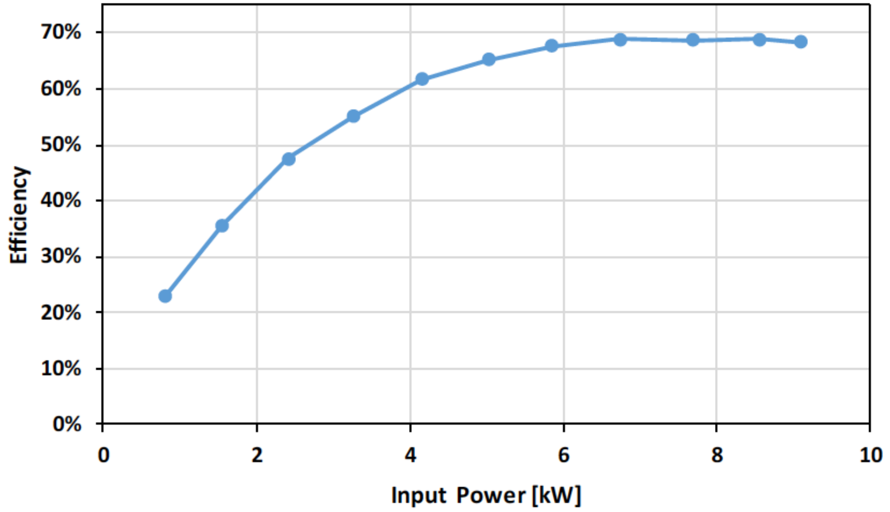
L3 MBIOT Factory Acceptance Results

Factory Acceptance test in October 2016 demonstrated the achievement of the main performances with some limitation due to the power supply at factory



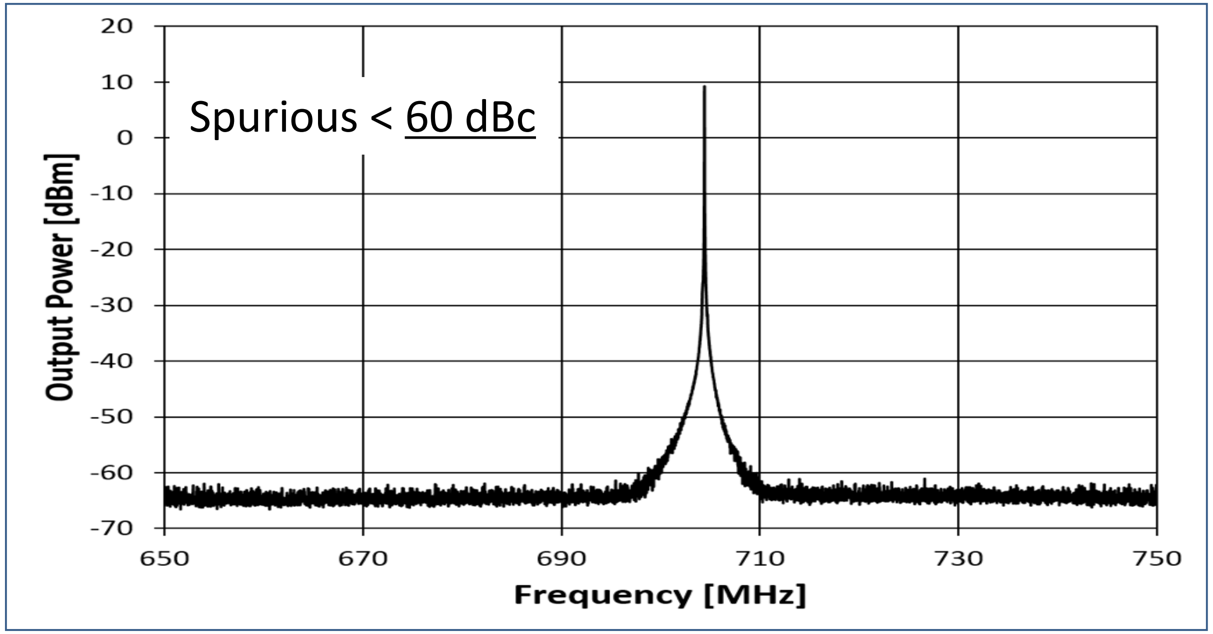
Transfer curve at -43.4 kV



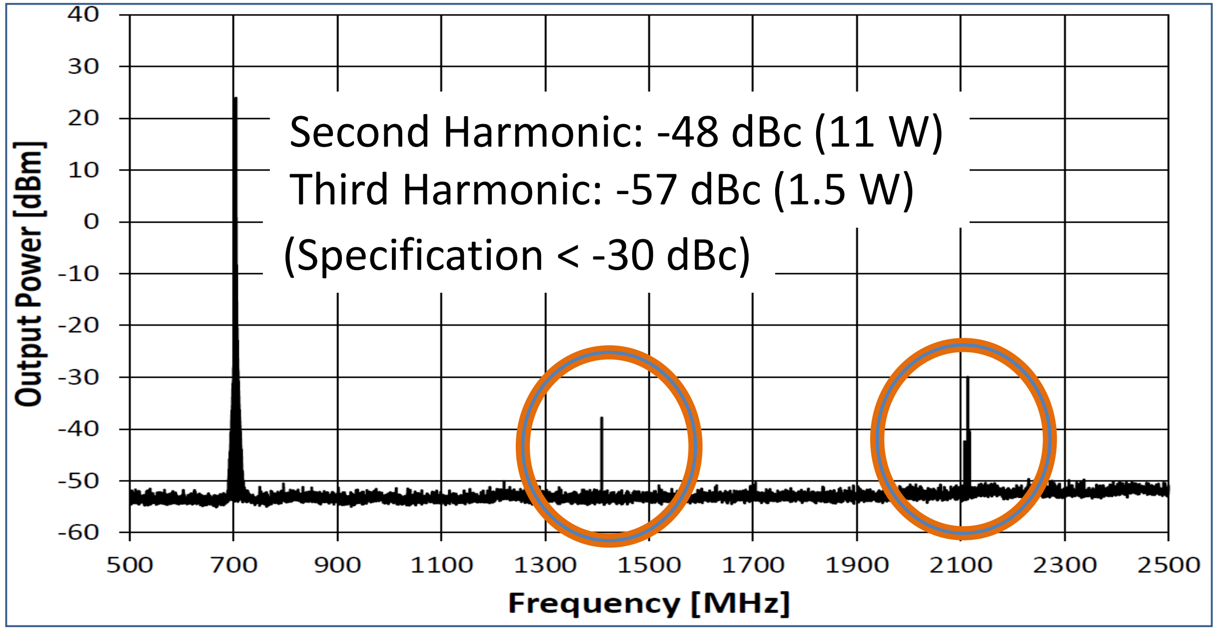


L3 MBIOT Factory Acceptance Results

Output spectrum at 1 MW



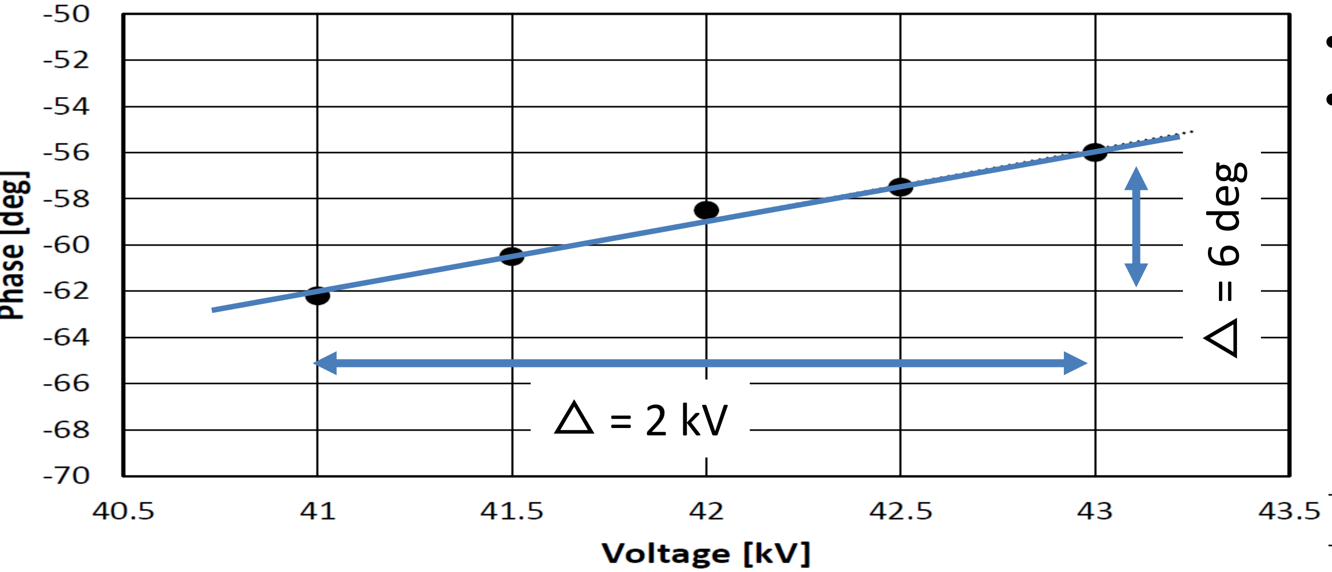
Harmonic content at 1 MW



(Coupling factors calibrated at harmonics)

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

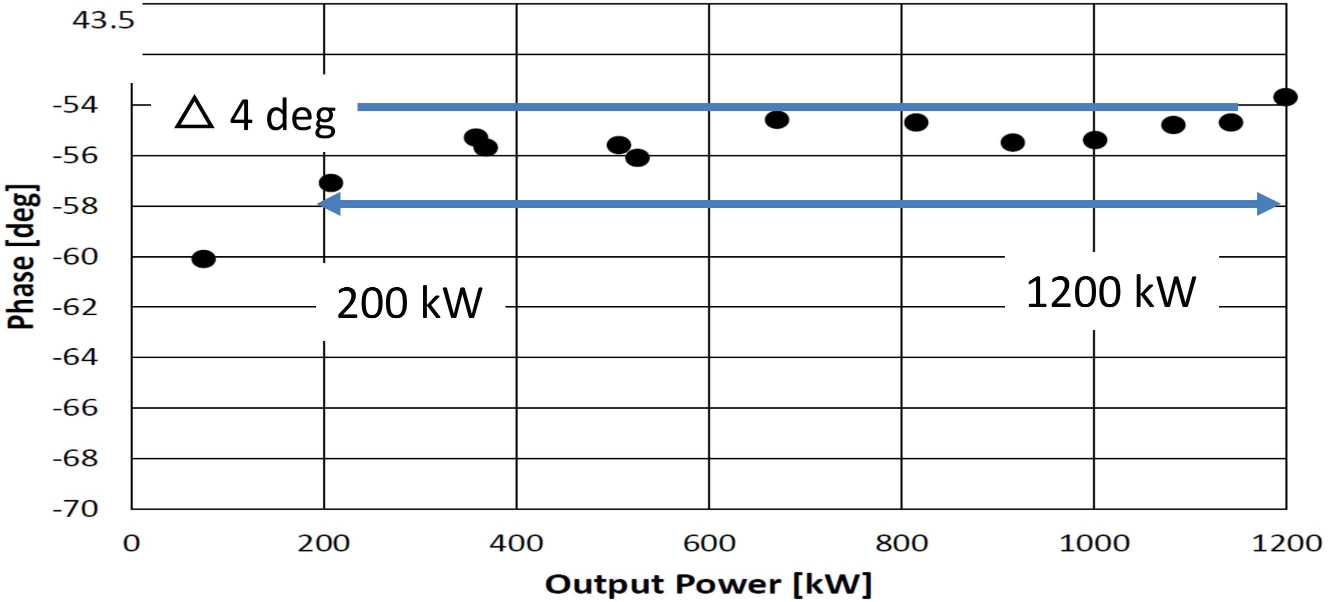
L3 MBIOT Factory Acceptance Results



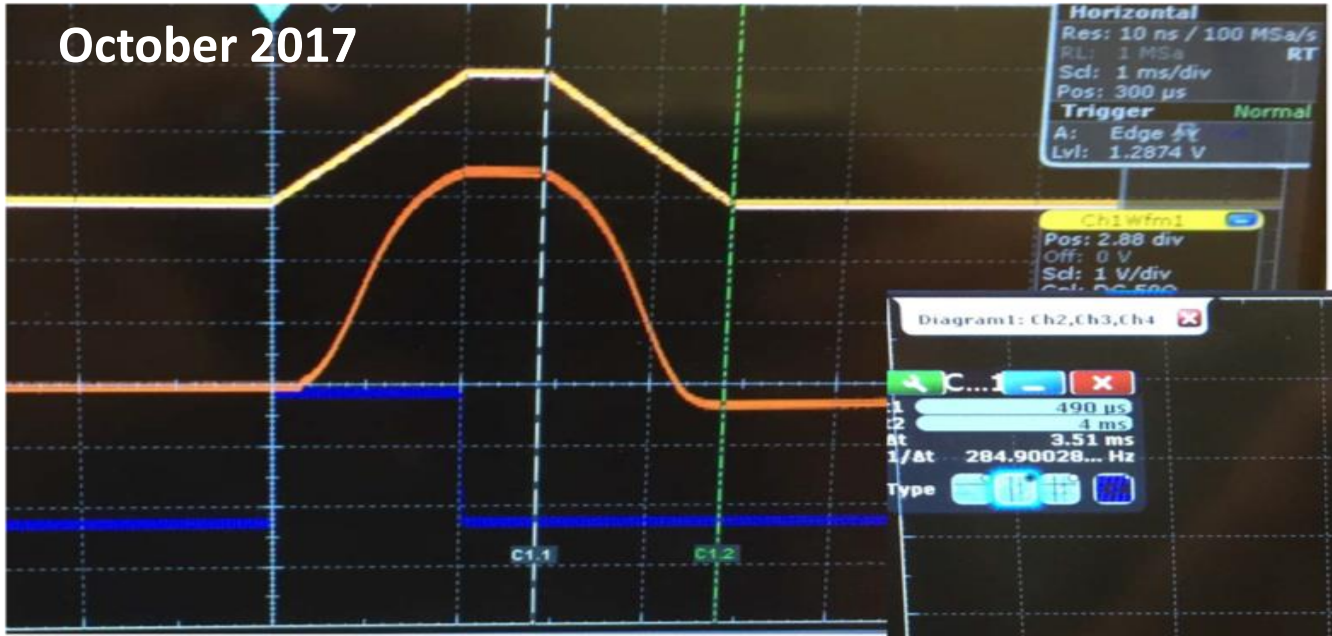
- **Low Insertion Phase: 3 deg / kV**
- **Linear and reduces phase variation due to HV ripple**

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

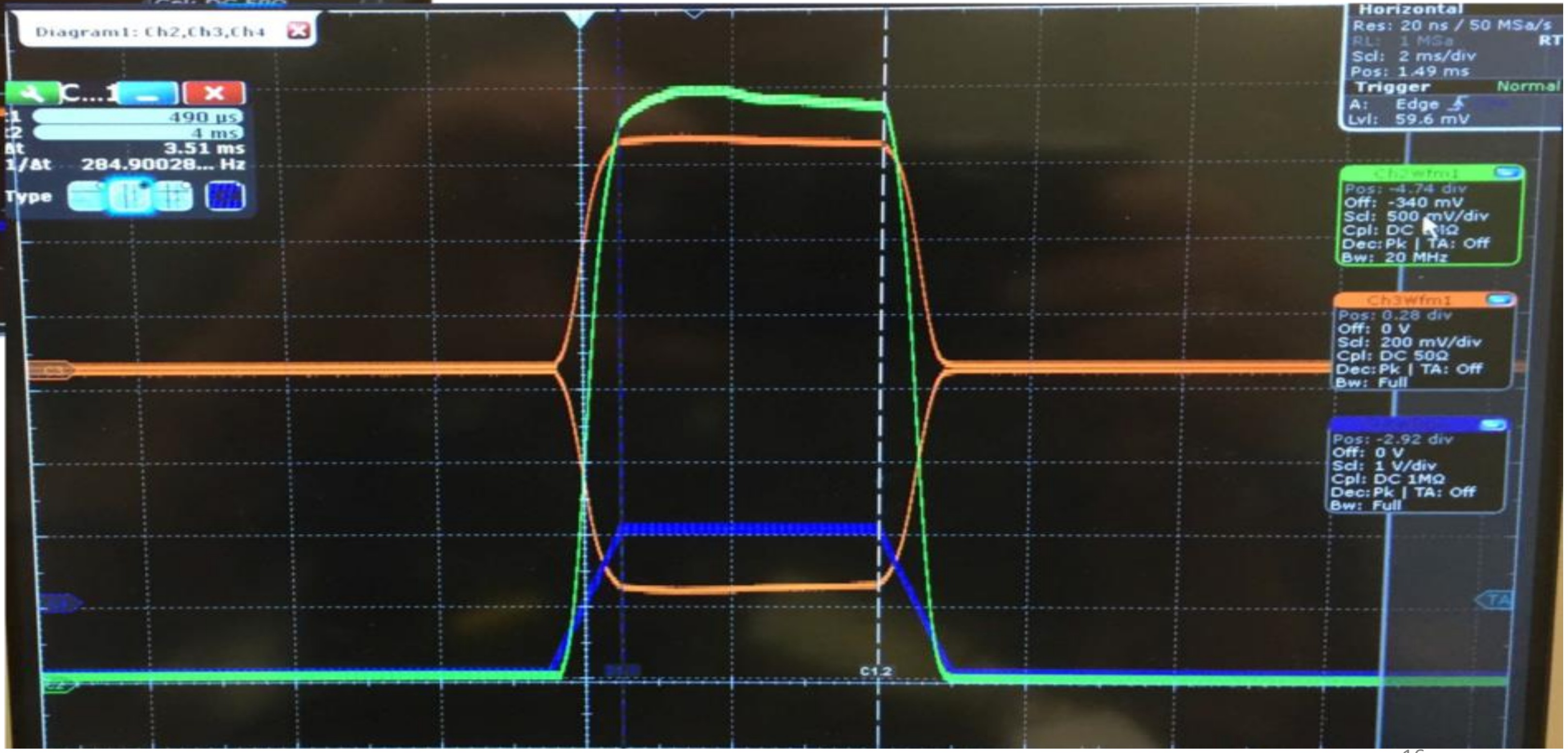
- **Monotonic phase shift for increasing output power**
- **Total phase shift < 4 deg from 20% to 100% of nominal output**
- **Measured at constant beam voltage**



L3 MBIOT Site Acceptance Test Results



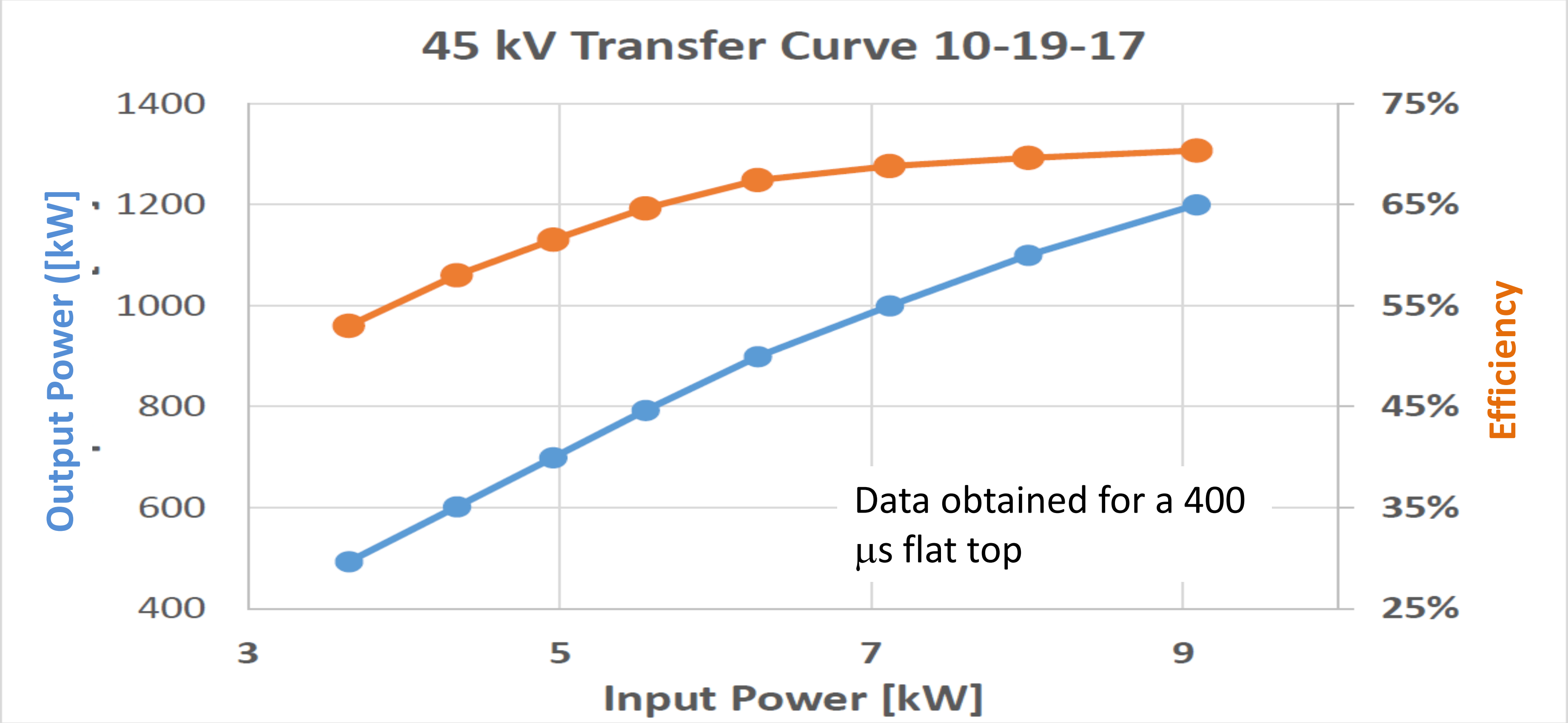
Scope capture with 400 µs flat top
Input Drive: Yellow trace
RF Output Power: Orange trace



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 MBIOT Site Acceptance Test Results

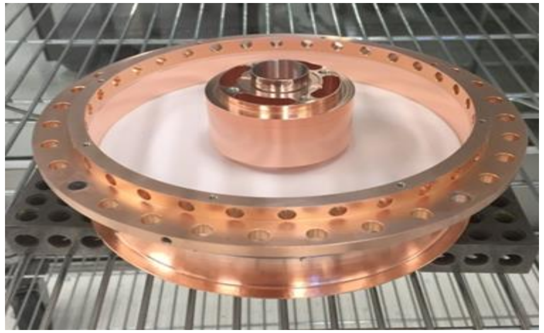


Long pulse operation:

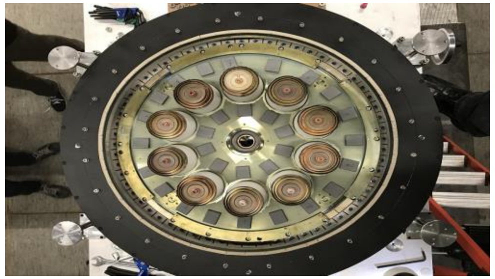
1.2 MW achieved with 3.5 ms flat top with 1 ms ramps on leading and training edges
1.14 MW achieved at 4 ms flat top, limited by the drivers

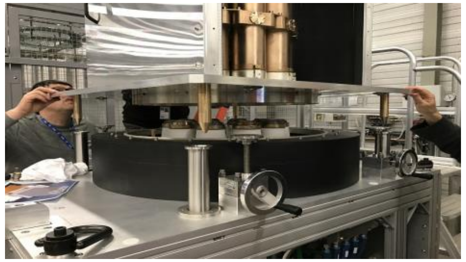
From Simulation to Reality: Thales and CPI

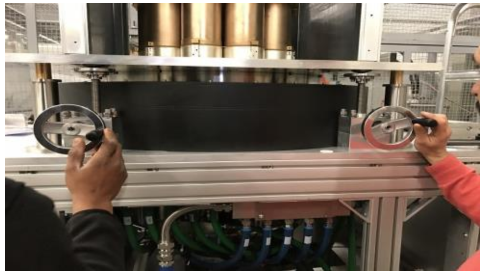
EUROPEAN SPALLATION SOURCE



- Solenoid focusing
- Single driver (tetrode), then split
- Gun, HV ceramic and input circuit by TED, tube assembly, magnet, output cavity, cart by CPI
- Coaxial window from HP pulsed klystron
- Full RF performance with less than 10 beams



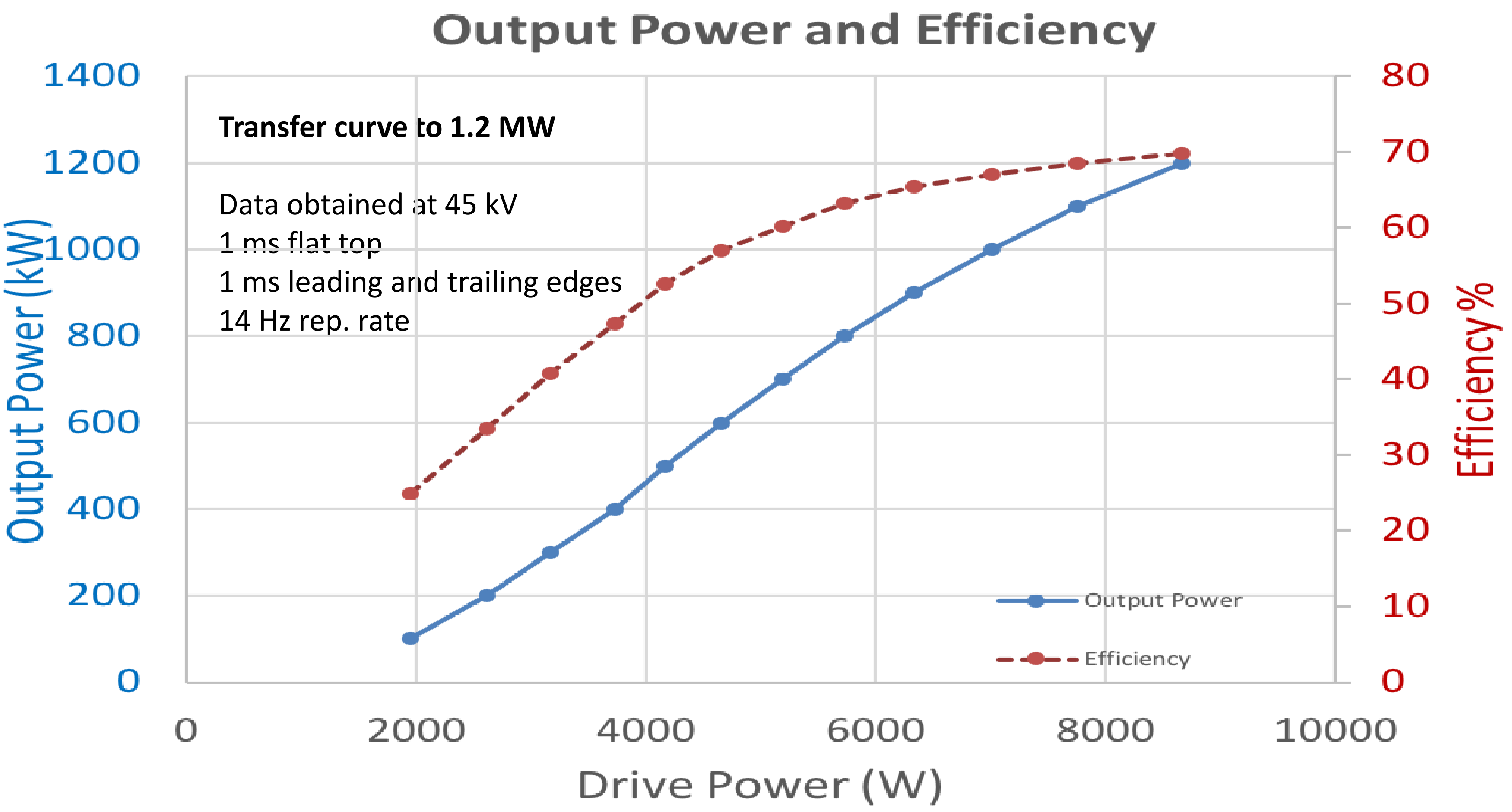


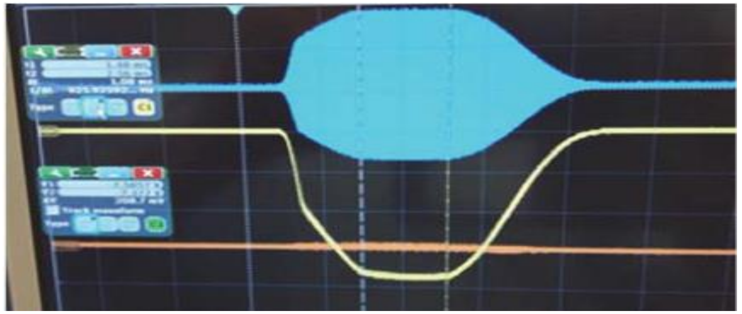


Assembly at CERN

TED/CPI IOT Results

EUROPEAN SPALLATION SOURCE

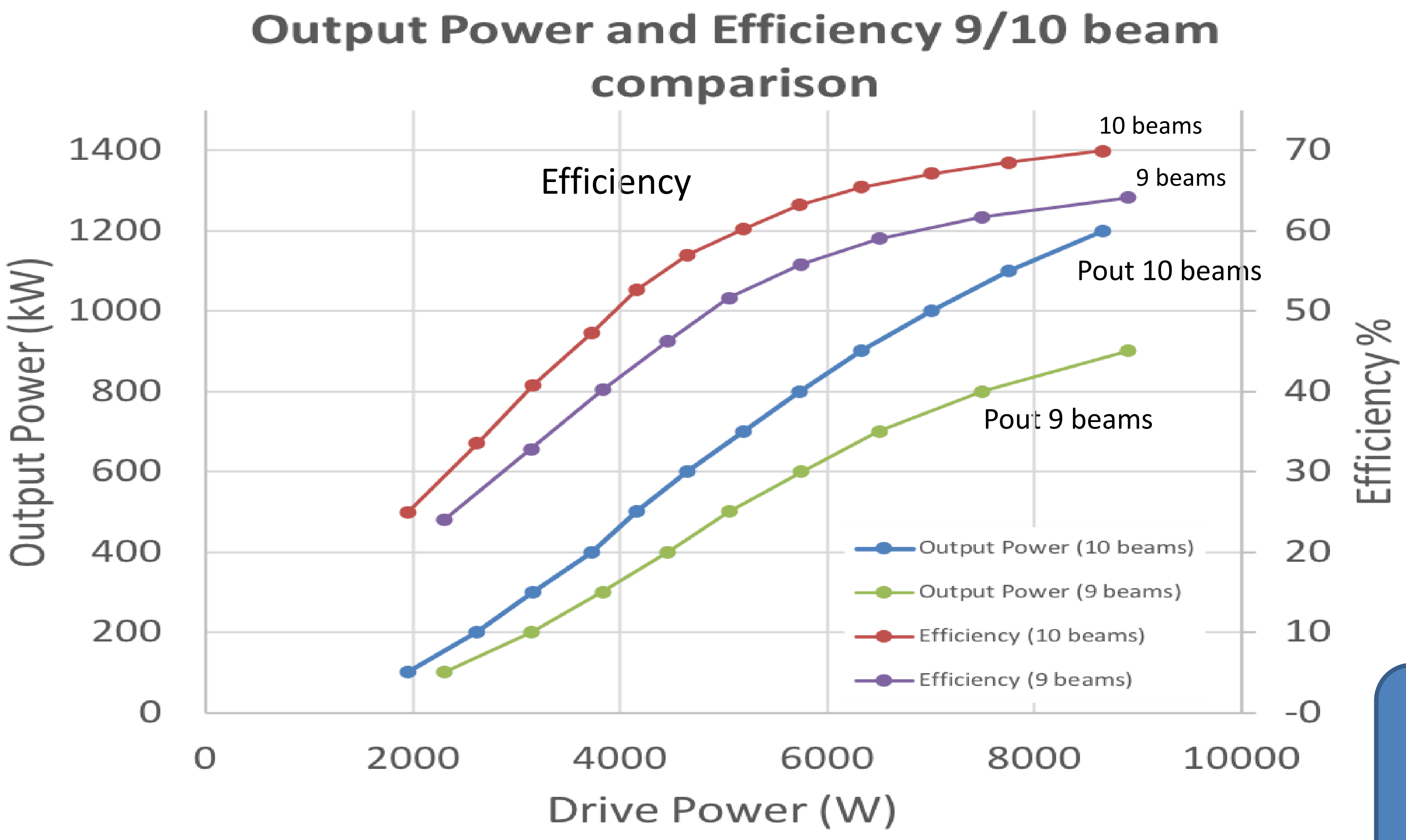




Yellow: Total Collector current
Blue: RF output pulse

IOT installed at CERN

TED/CPI IOT Results



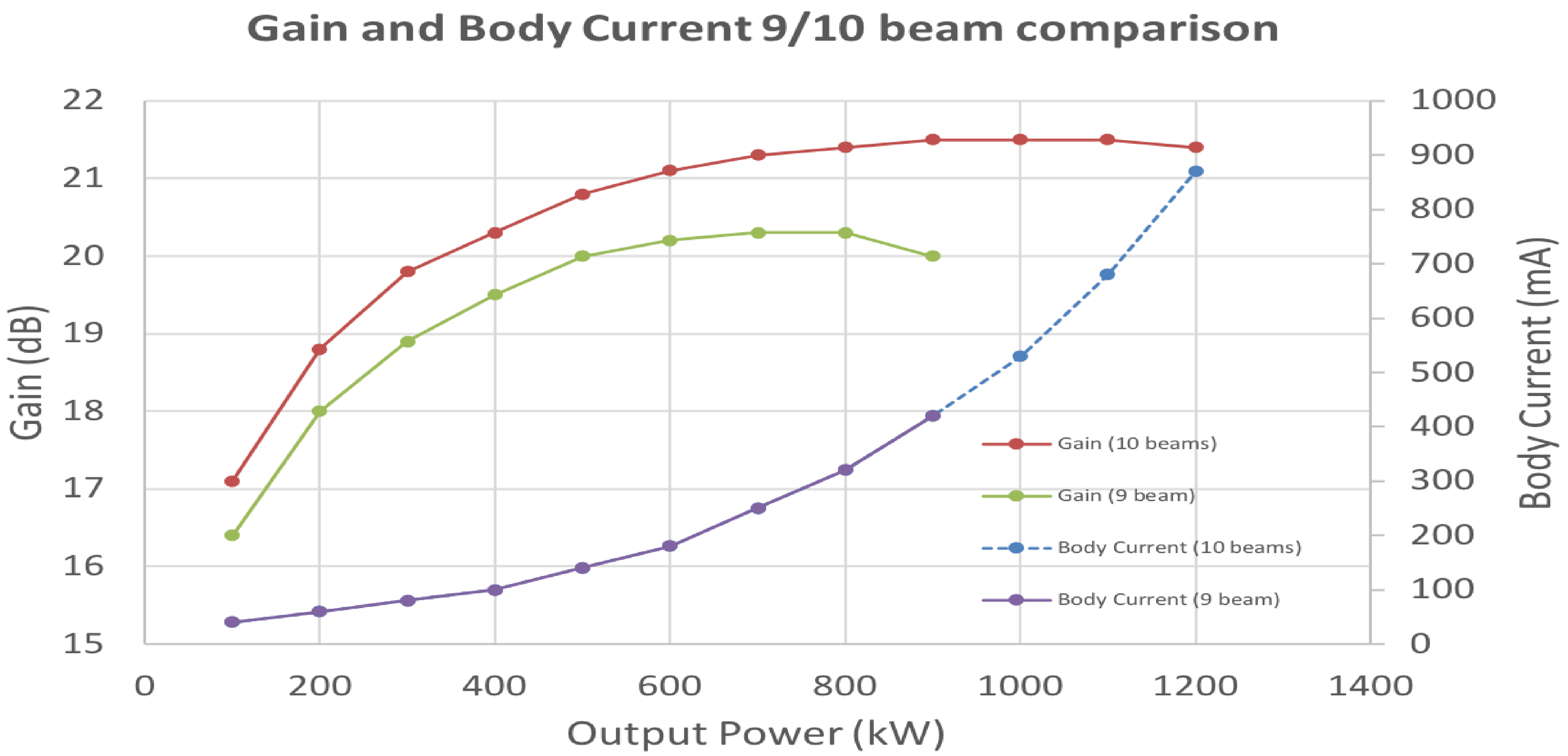
One gun off
Input cavity removed.

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



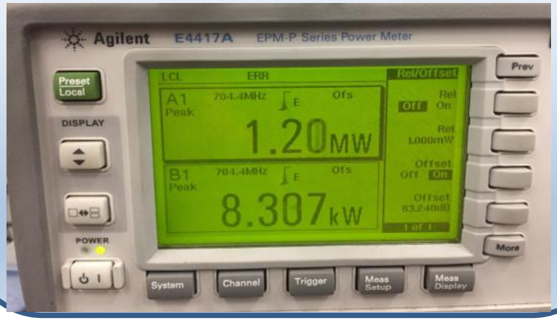
MBIOTs testing at Cern

MBIOTs delivered to CERN for testing

Both MBIOTs have delivered 1.2 MW

Overall Technical Specification achieved

World Record



Thales/CPI MBIOT

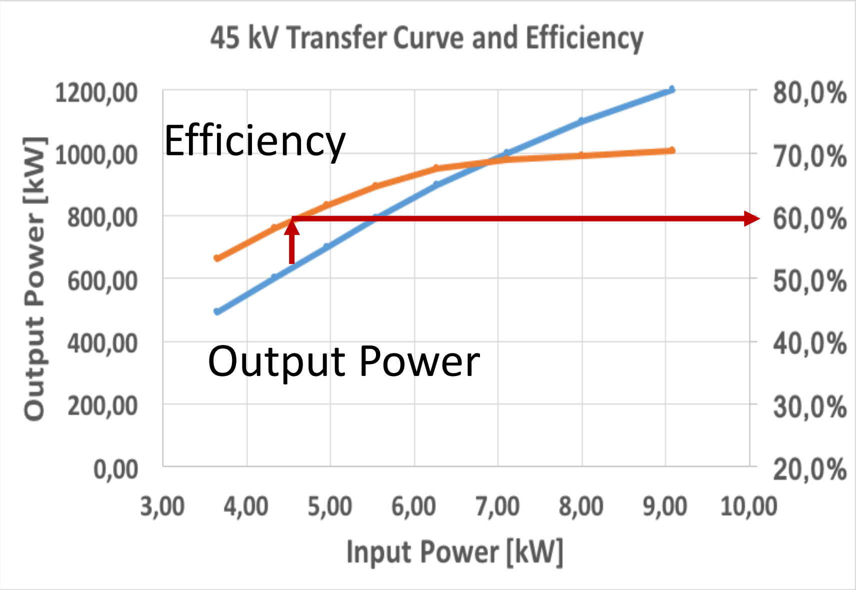
Testing at CERN

L3 MBIOT

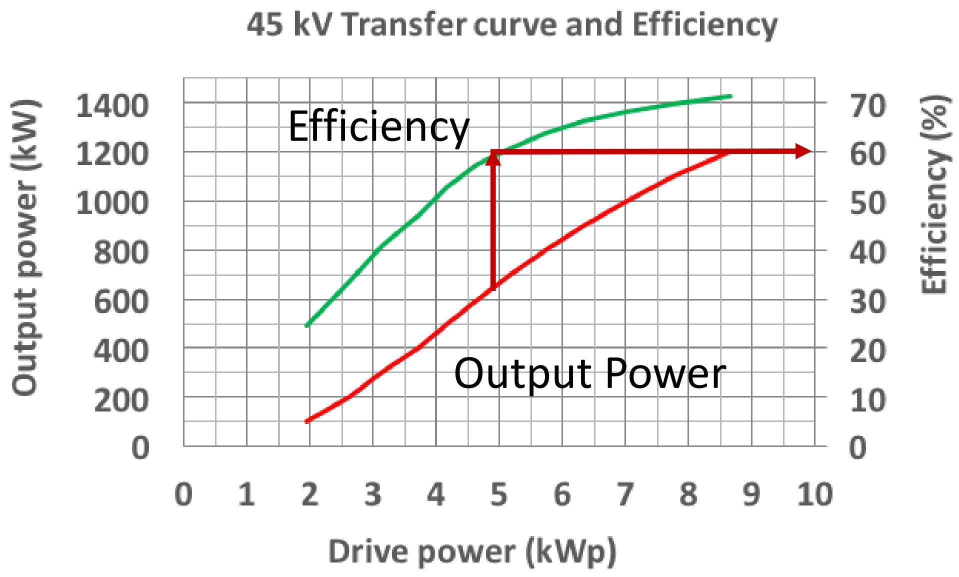
Results of the MBIOT testing

Summary

L3 MBIOT



Thales/CPI MBIOT



70 % efficient at 1.2 MW

Efficiency remains > 60% from 650 kW

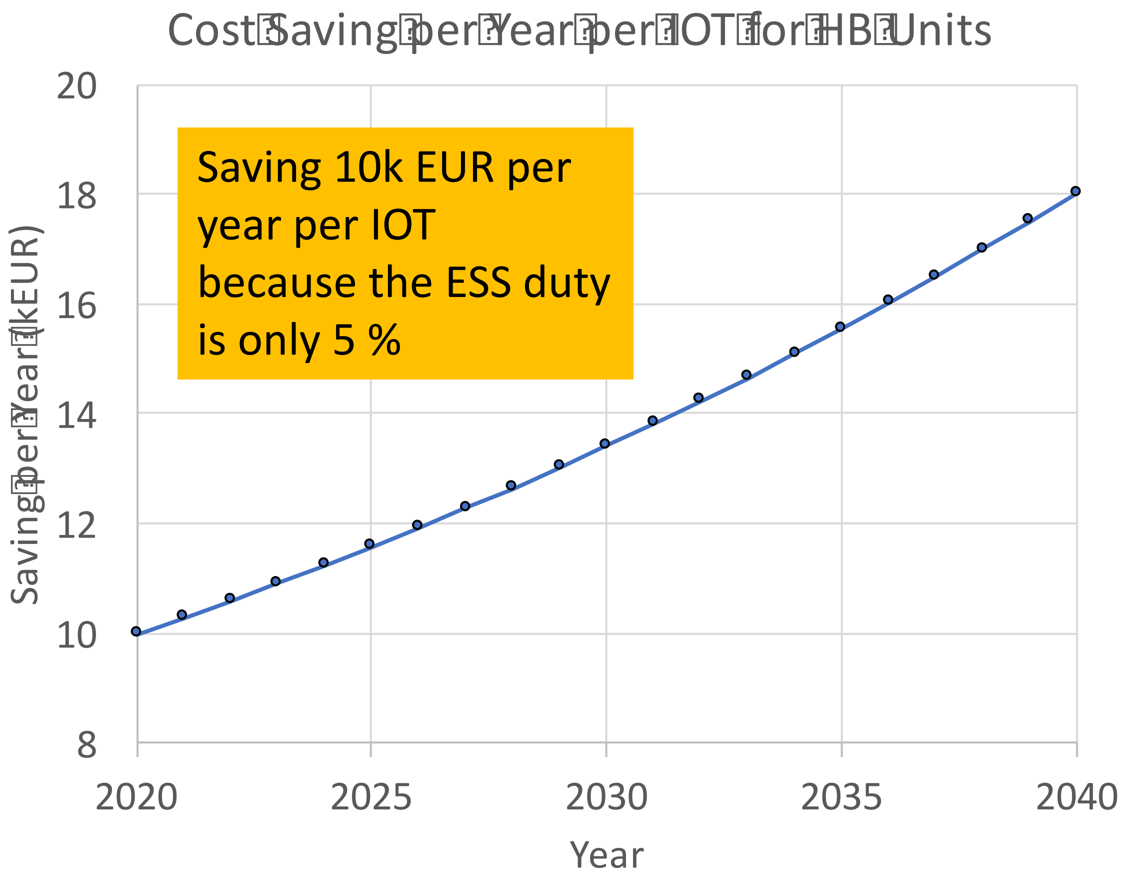
Further optimisation possible by optimising HV and Q

High efficiency at point of operation even when overhead is required

Comments after some operational experience

- Initial test setup was not trivial
- Care needed with configuration and design of drivers and auxiliary devices incl. filament, focussing and ion pump supplies
- Both IOTs delivered 1.2 MW
- Both IOTs demonstrated possibility of operating with fewer guns in operation
- Dedicated developments for HV PSU, auxiliary supplies are needed to optimise operation
- Some industrialisation needed to reduce cost, ease operation and improve operational stability
- The MB-IOT is particularly relevant for high duty and high power facilities where a power overhead is required for regulation

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

Final decision was to use klystrons also for high beta
MBIOT technology is promising but needs more time to mature

Summary

Conclusion and future developments

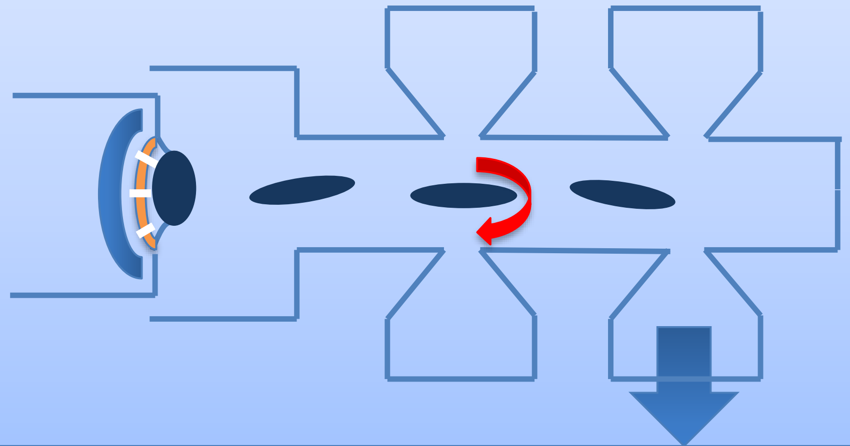
- IOT is an efficient power source, especially when considering the operational efficiency
- High power limitation can be somehow overcome by the use of MB IOT
- The MBIOT development for ESS was successful but not mature enough for the ESS timeline
- The technology is however now available for other users!
- Further improvements are possible: High efficiency klystron research can be applied to IOTs as well to increase the efficiency even more.

- High voltage, 1 MW, single cathode
- 10 MW MBIOT by combination of 1 MW tubes

What else could we achieve?

- More power
- Higher efficiency
- Better reliability
- Smaller footprint, etc.

Grid controlled emission with bunch forming cavities
HE-IOT (from 75% to…. 90%)
Grid controlled emission + “rotating” cavity + output cavity



Thank you for your attention!

And special thanks to:

- Morten Jensen (from whom most of the presentation material comes from)
- L3
- Thales/CPI