High Power IOTs

Morten Jensen

The Inductive Output Tube

Invented in 1938 by Andrew V. Haeff as a source for radar

- To overcome limitation of output power by grid interception
- Pass beam trough a resonant cavity
- Achieved: 100 W at 450 MHz, 35% efficiency

Used first in 1939 to transmit television images from the Empire State Building to the New York World Fair

IOTs then lay dormant

- Intense competition with velocity modulated tubes (klystron had just been invented by the Varian brothers)
- Difficult to manufacture

The IOT is often described as a cross between a klystron and a triode hence Eimac's trade name 'Klystrode'

Why use IOTs

- ✓ High efficiency at point of operation
- ✓ Small
- ✓ Power is pulsed by RF instead of HV
- ✓ Good Linearity
- X Lower Gain

Good for machines which require the amplifier to operate at different power levels

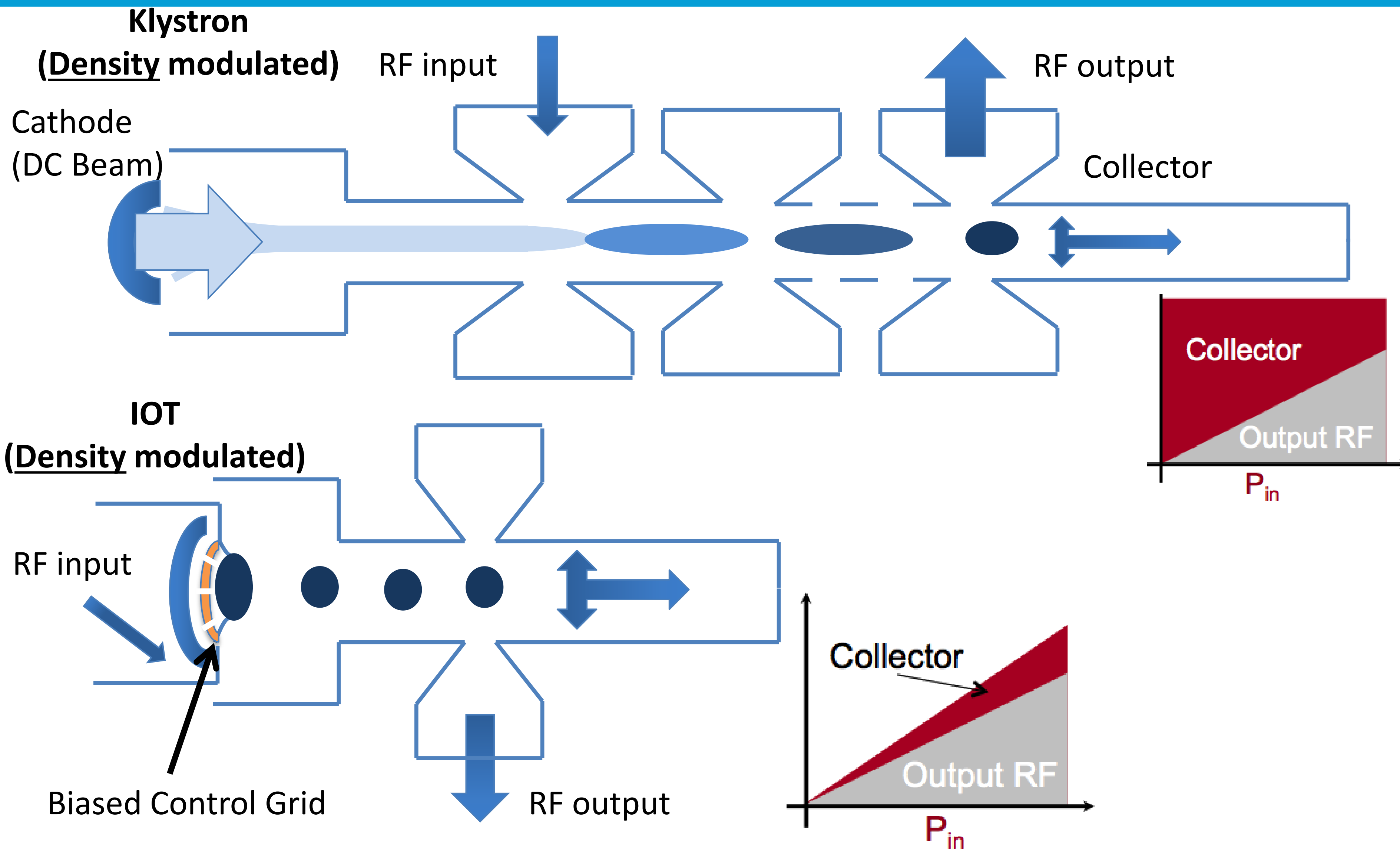
- varying power loads
- Non uniform power profiles
- Margins for overhead for regulation
- One-to-one relationship with amplifier to accelerating structure

Proton Linacs in particular can benefit

Circulating machines with high regulation requirements

Often what prohibits technology is the lack of demand

The Main Principles



IOT and Klystron Comparison

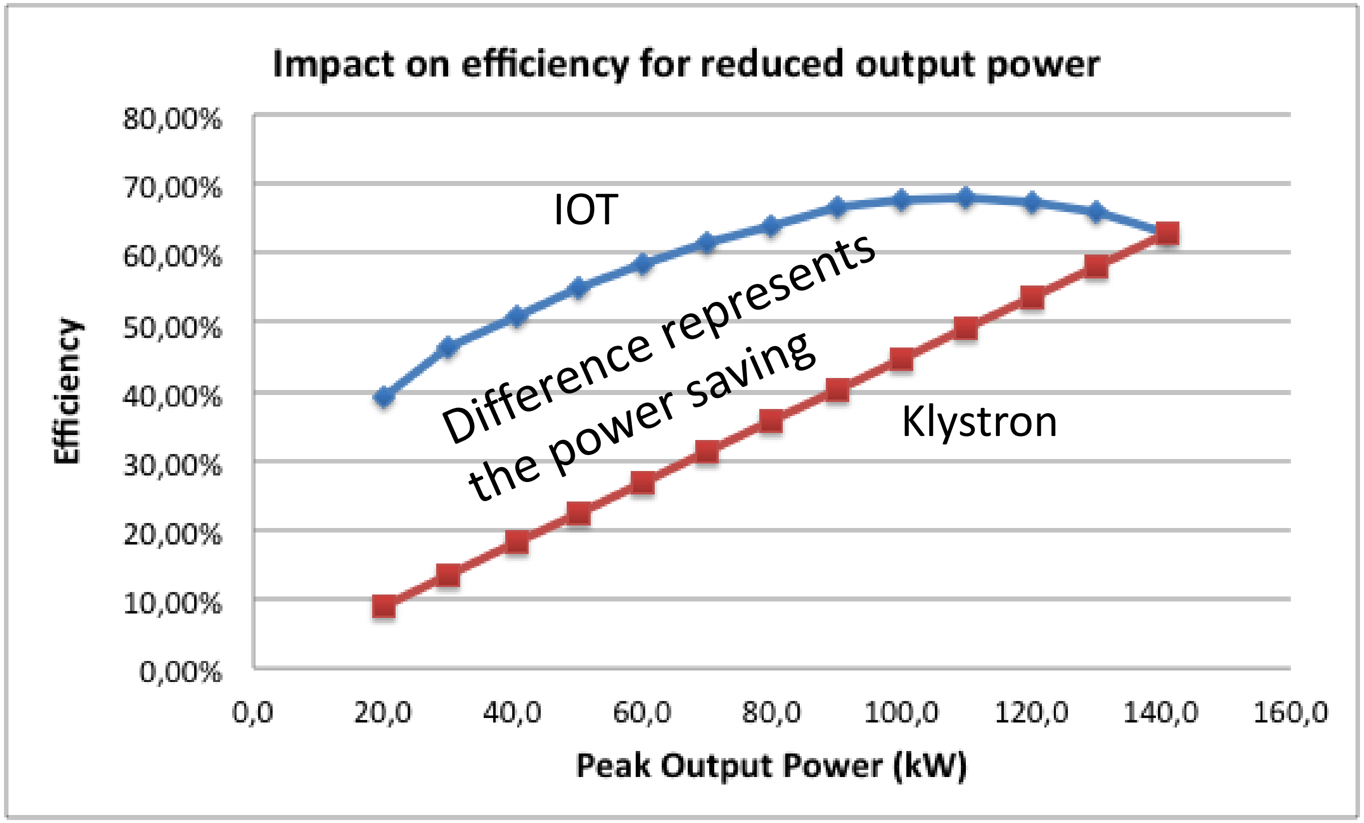
Klystrons:

- Velocity modulated DC beam
- Maximum theoretical efficiency is 100%, same as for Class C amplifier
  - Beam to be infinitely short
  - Cross the gap in zero time
  - Space charge reduces efficiency
  - Efficiencies of > 80% possible but 65% typical at saturation
- Klystron saturates at maximum power
- Efficiency drops rapidly for operation at reduced output (DC input is constant)
- Collector has to handle full DC beam (e.g. at Eff. 50% Pcol = twice RF power)

IOTs:

- Density modulated beam
  - Grid controls current
- Maximum theoretical efficiency is also 100%
  - Needs zero length bunches which means zero current!
  - Cross the gap in zero time
  - Class B operation more common, efficiency 70-75% typical
- IOT does not saturate as a klystron
- Efficiency drops slowly at reduced output power
- Low pushing factor; helps power supply design
- Collector only ever handles spent RF beam (e.g. at Eff. 50% Pcoll= RF power)

Efficiency comparison of Klystrons and IOTs

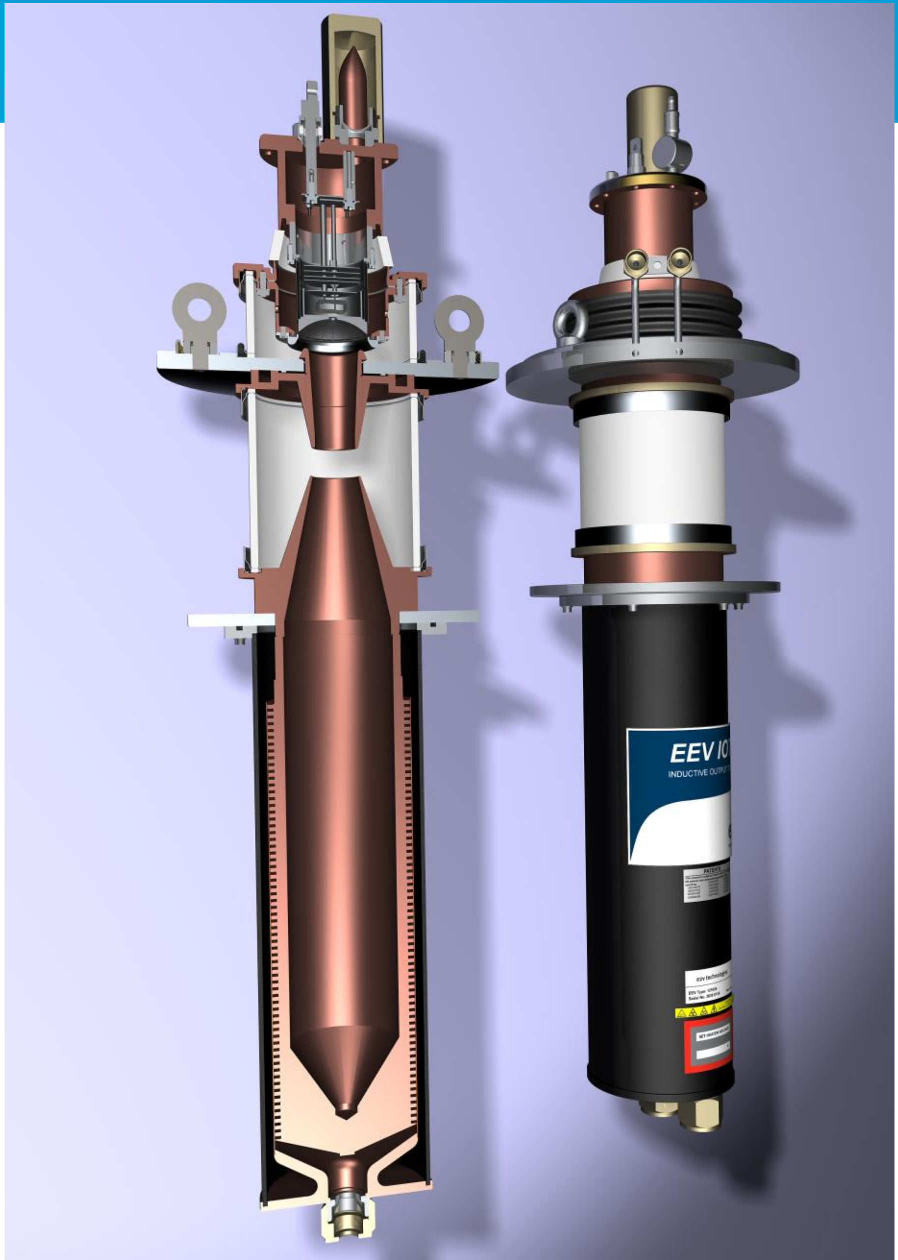


IOT measurements courtesy of M. Boyle, L3

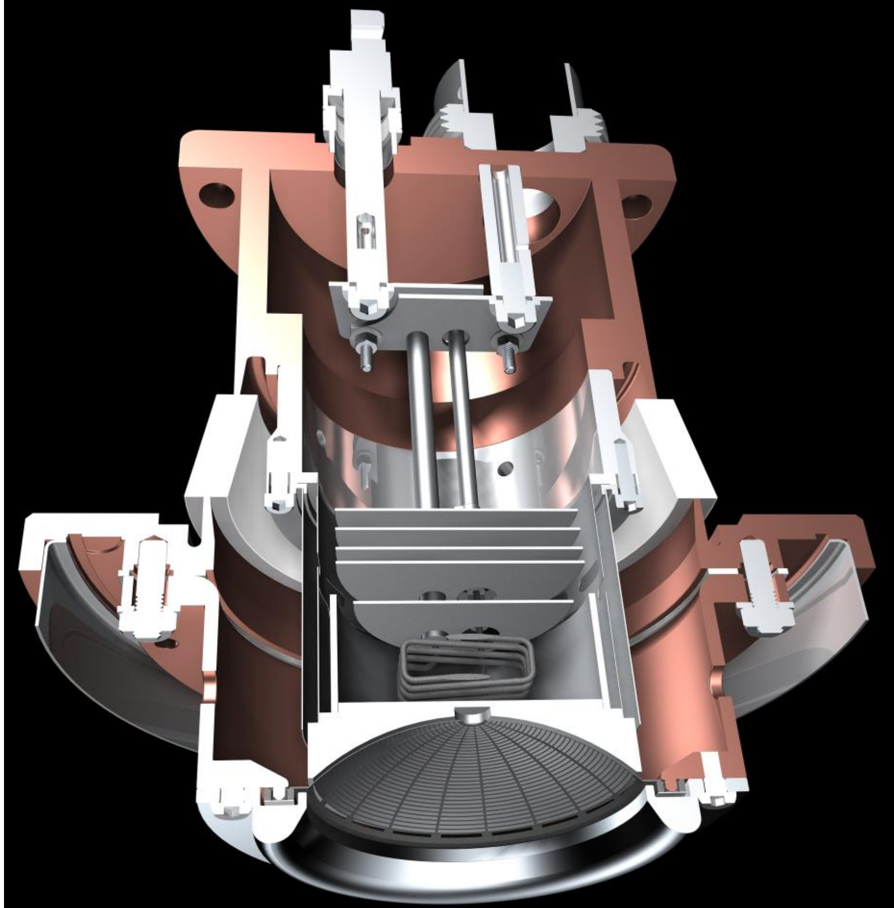
- Based on broadcast IOT L-4444
- System setup limited by drive power and beam voltage
- IOT setup for maximum gain (not efficiency) without breakdown
- No optimisation of coupling, grid voltages etc. for different power levels

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

Typical Broadcast IOT



Courtesy of e2v



3rd Generation Light Sources

Three 500 MHz 300 kW amplifier for Storage Ring: 4 x 80 kW IOT combined
One 80 kW for the Booster
IOTs from E2V

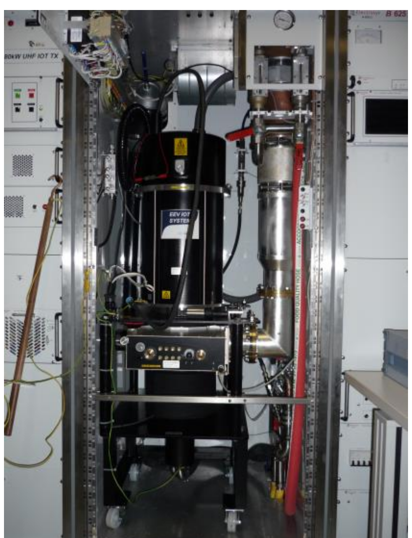
6 RF plants of 160 kW
500 MHz
2 IOTs combined per cavity
IOTs from Thales Electron Devices and L3

Selection of other Facilities using IOTs

NSLS II
L3 IOT, 500 MHz
80 kW CW

CERN
800 MHz
60 kW

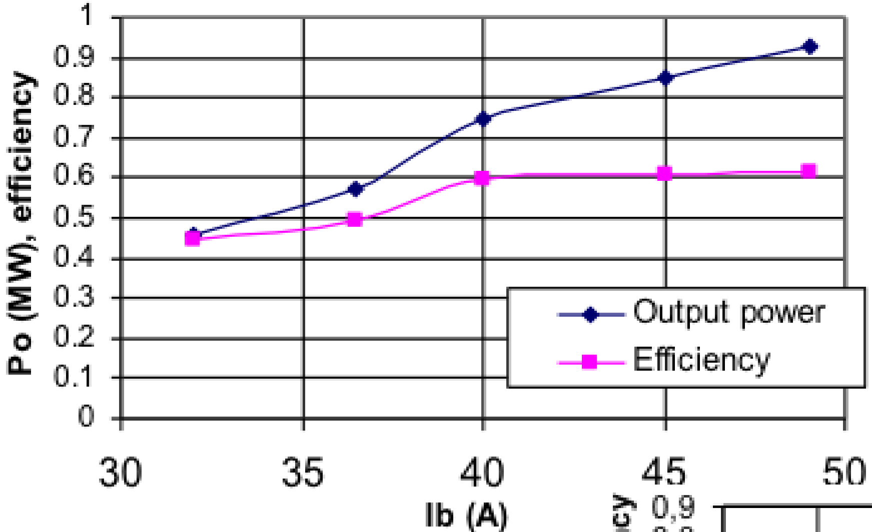
Metrology Light Source
(Willy Wien Laboratory)
CPI 90 kW IOT (K5H90W1)



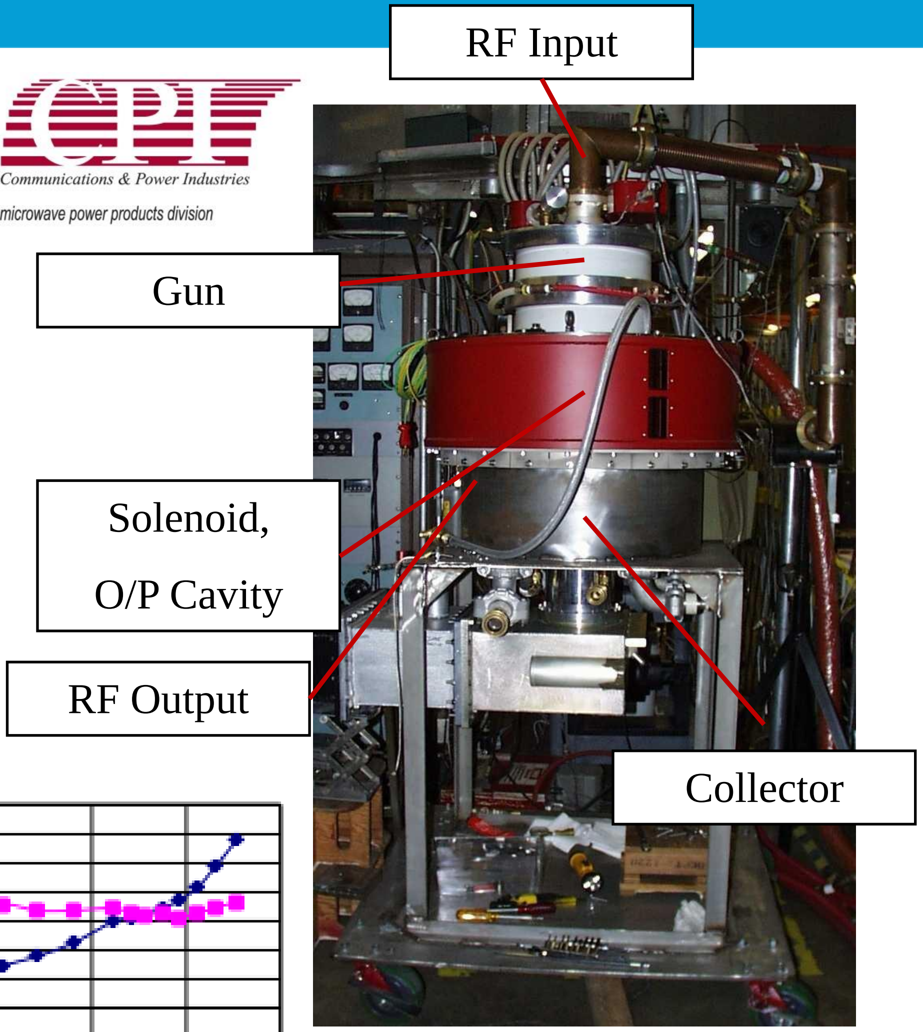
Elettra
500 MHz
150 kW IOT based amplifier
for Combination of 2x80 kW

700 MHz HOM IOT Experience

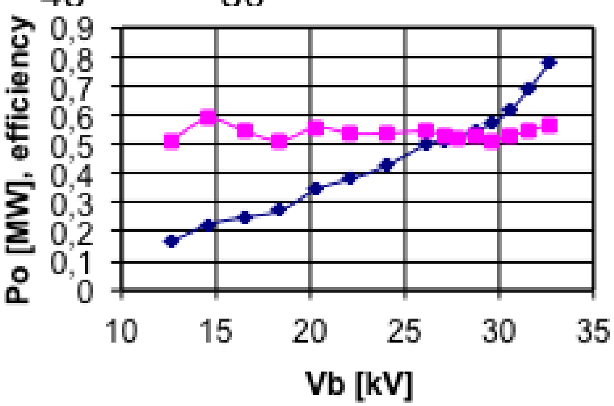
Design Parameters	value	units
Power Output	1000	kW (min)
Beam Voltage	45	kV (max)
Beam Current	31	A (max)
Frequency	700	MHz



Communications & Power Industries
microwave power products division



Test Results (pulsed)



VHP-8330A IOT

Other IOT technology

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IOTs designed for various applications
Series production has been < 100 kW

CPI
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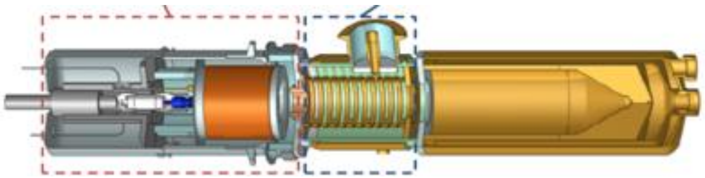
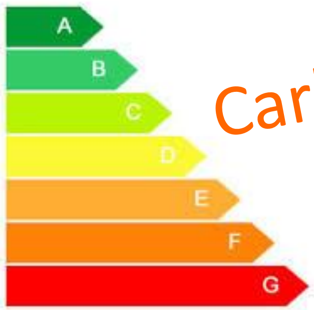
267 MHz
300 kW CW

Depressed collector IOTs



L3 wide band IOT

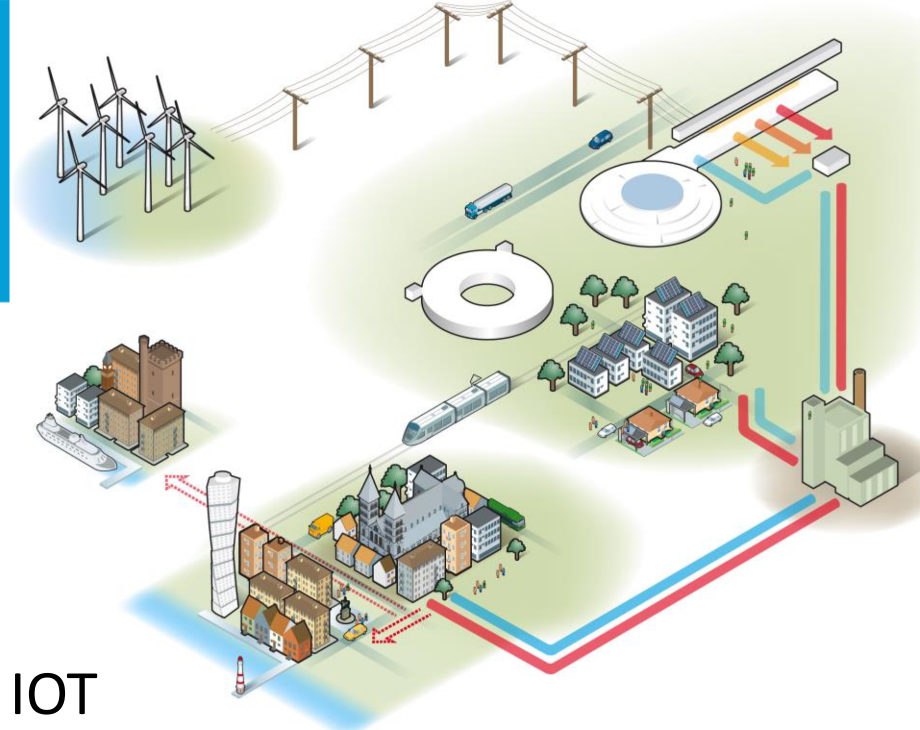
The ESS Requirement



Carbon Neutral

Innovative

Green



Opportunity to develop Super Power IOT

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	84	1100**

** Plus overhead for control

The ESS Superconducting Power Profile
> 150 cavities/couplers

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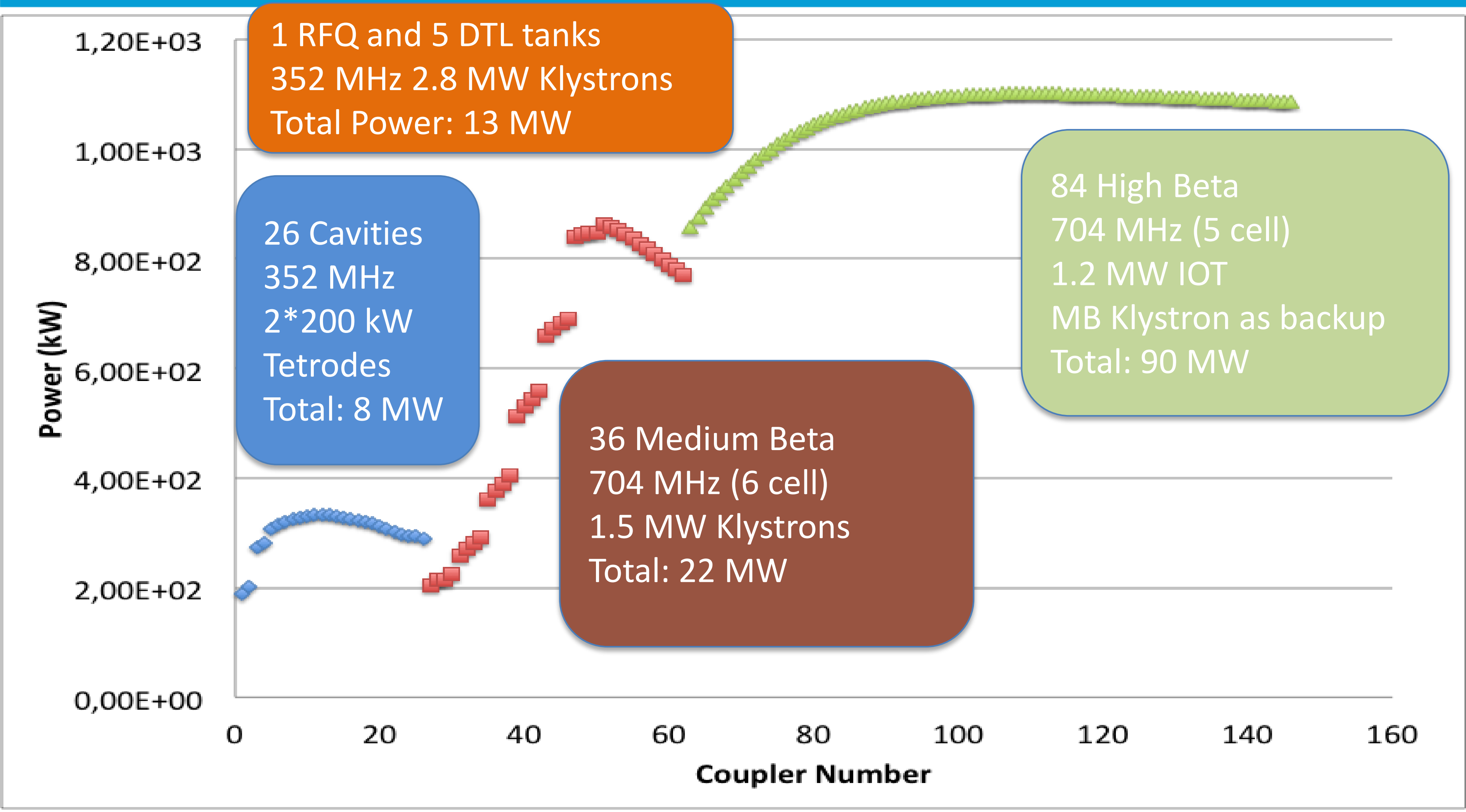

Total High Power RF: 133 MW peak (4% duty) plus overhead

An IOT for ESS

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Parameter		Comment
Frequency	**704.42 MHz**	**Bandwidth > +/- 0.5 MHz**
Maximum Power	**1.2 MW**	**Average power during the pulse**
RF Pulse length	Up to 3.5 ms	Beam pulse 2.86 ms
Duty factor	Up to 5%	Pulse rep. frequency fixed to 14 Hz
Efficiency	Target > 65%	
High Voltage	Low	Expected < 50 kV
Design Lifetime	> 50,000 hrs	

Work is being carried out in collaboration with CERN

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

Target: Approval for ESS series production in 2017/18

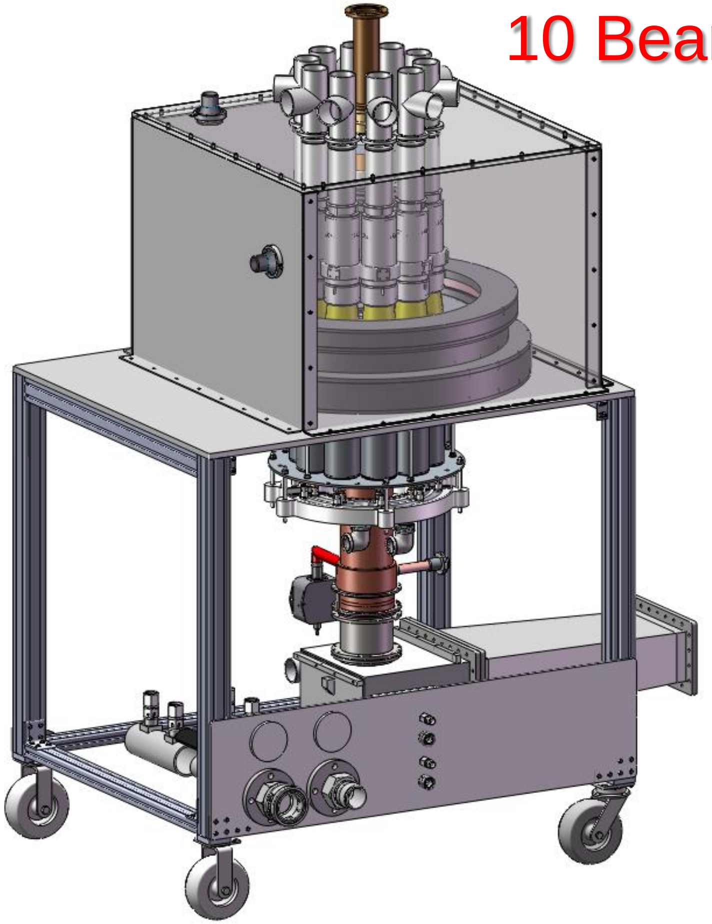
3.3 MW power reduction by using IOTs for High Beta

Two IOTs to be delivered in 2016

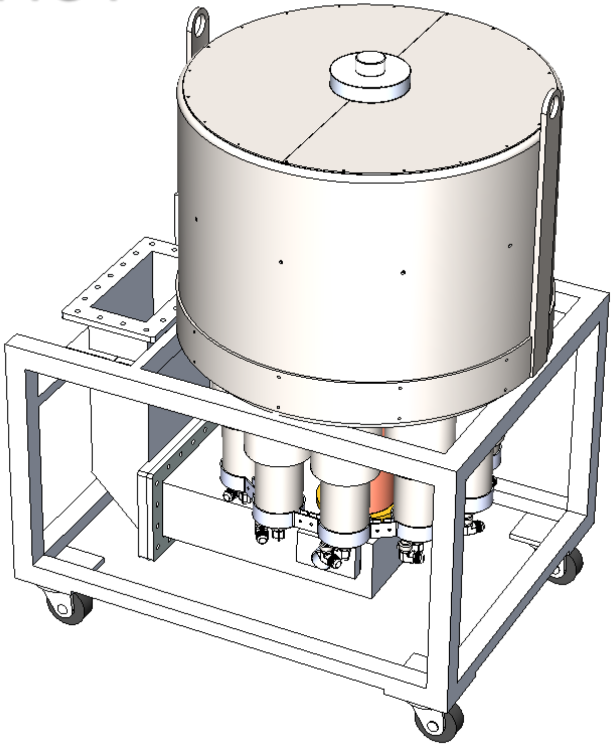
EUROPEAN SPALLATION SOURCE

- Two Multi-Beam IOTs being designed
  - Thales/CPI Consortium
  - L3
- Contracts signed in September 2014
- Project duration: 24 months
- Long term testing at CERN
- Approval for series tender 2017/18

Multi-Beam IOTs for ESS



10 Beam Multi-Beam IOT
1.2 MW
704 MHz



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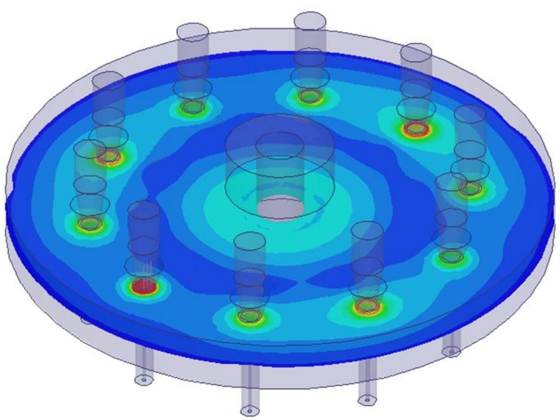
Output Cavity and DC Beam Studies Courtesy of L3 Communications

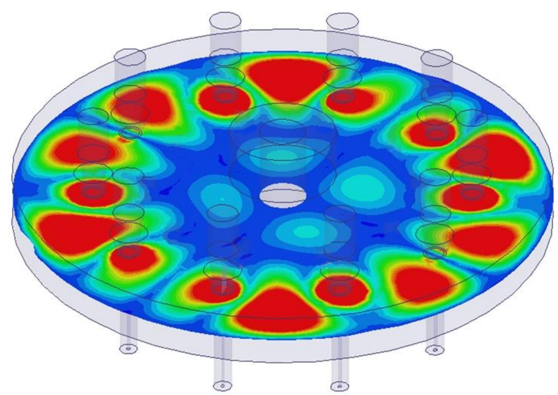
- Ten beams on a single bolt circle
- Output cavity supports a large number of modes
- HFSS used to map modes near harmonics of the drive frequency

Fundamental



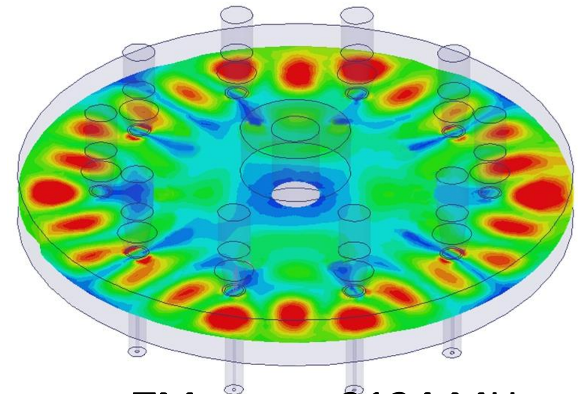
$TM_{1,0,0}$ at 704 MHz

Near Second Harmonic

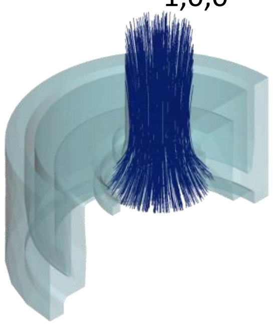


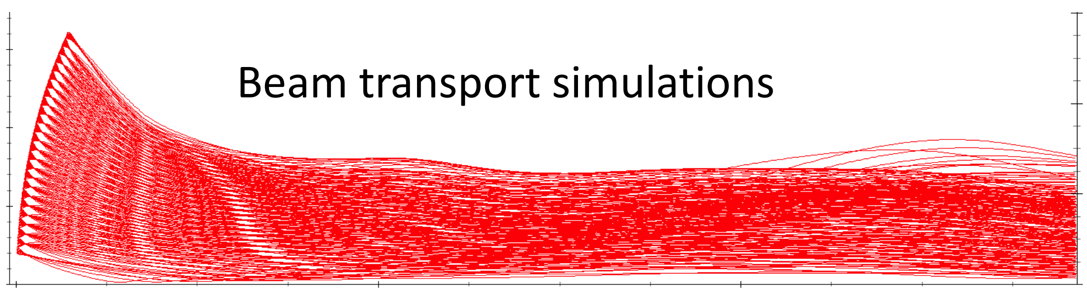
$TM_{1,16,0}$ at 1417 MHz

Near Third Harmonic



$TM_{1,24,0}$ at 2124 MHz





Beam transport and RF Interactions
Courtesy of L3 Communications

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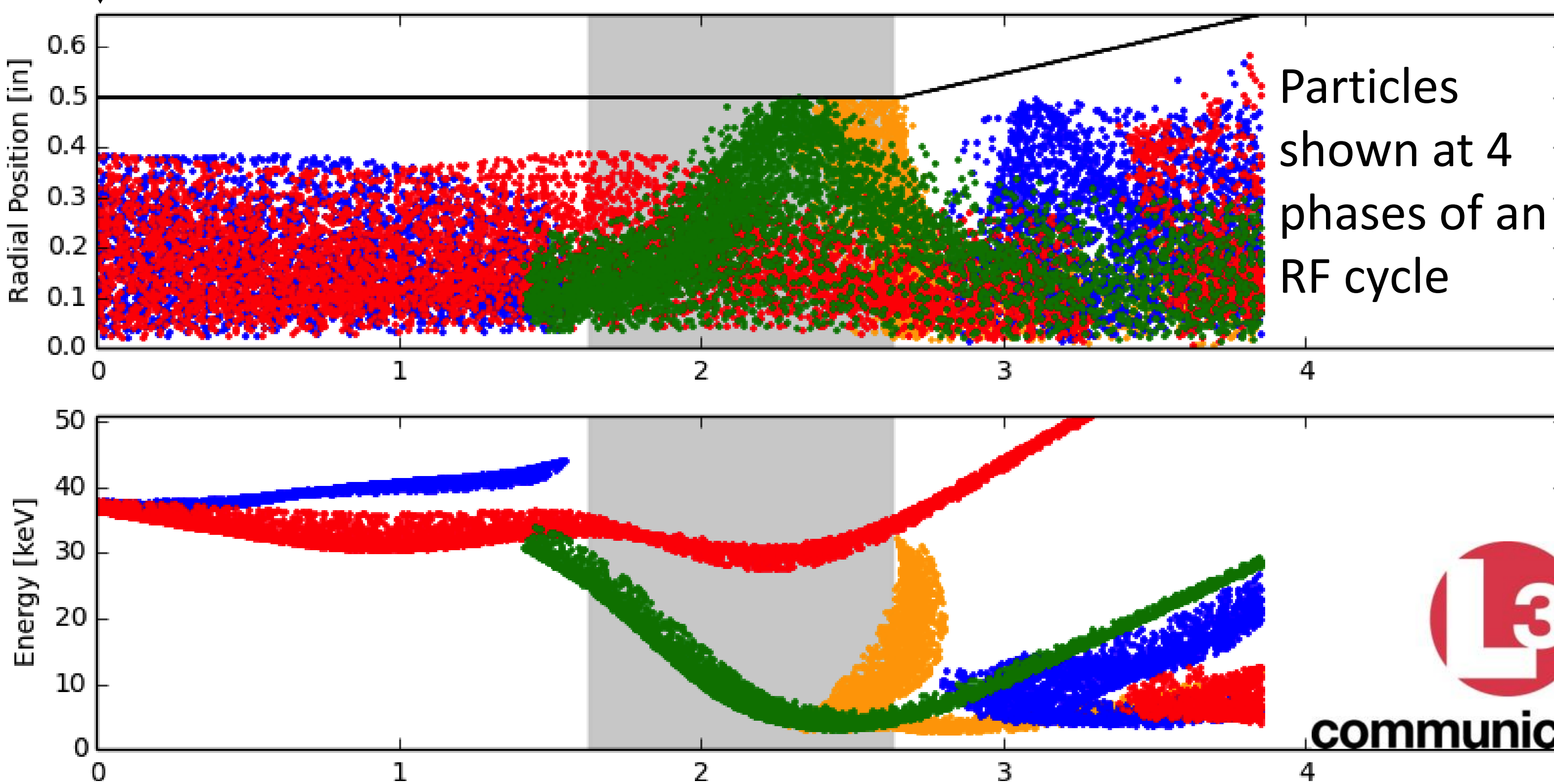
Beam profile imported here

Propagated in the presence of the magnetic field imported from Maxwell

Drift tunnel

Output Gap

Drift tunnel taper

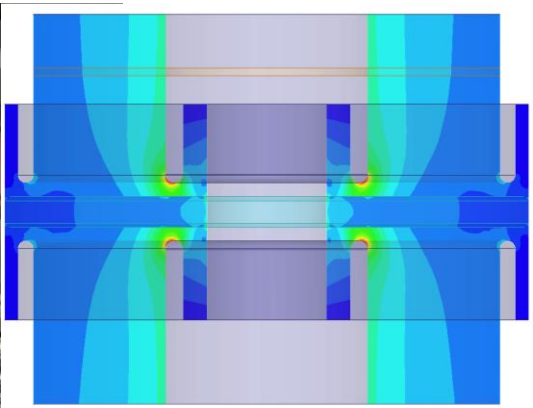


Particles shown at 4 phases of an RF cycle

communications

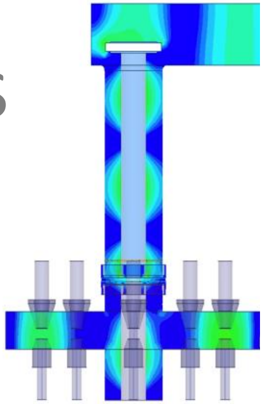
RF Output Circuit and Output Window Courtesy of L3 Communications

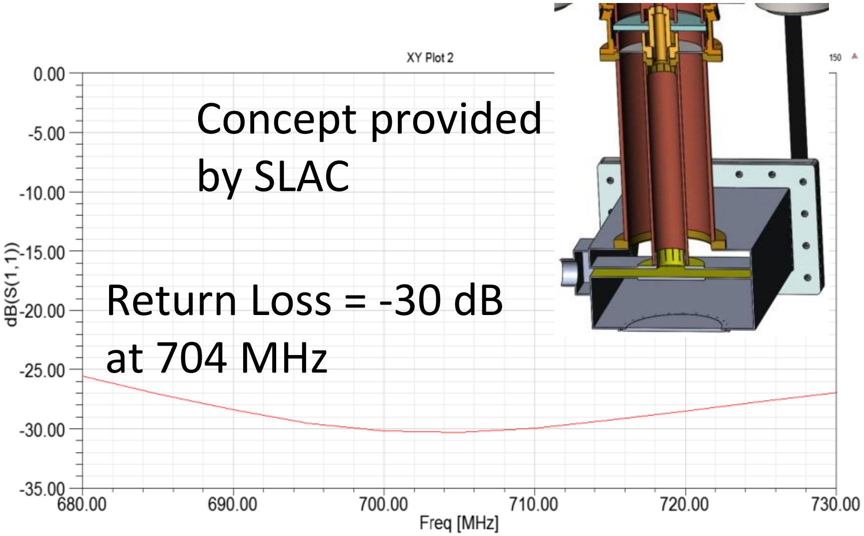
- Air cooled SLAC design Coaxial window from B-factory klystron
  - 1.2 MW CW operation, 476 MHz
  - TiN coated and has modest peak electric field



SLAC Proprietary

- T-bar Coax-to-Waveguide transition in air
- Design was rescaled for 704 MHz using HFSS





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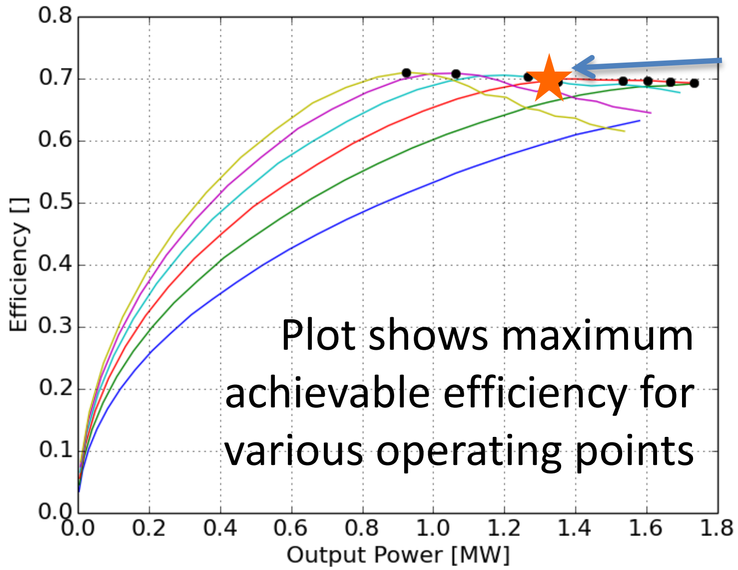
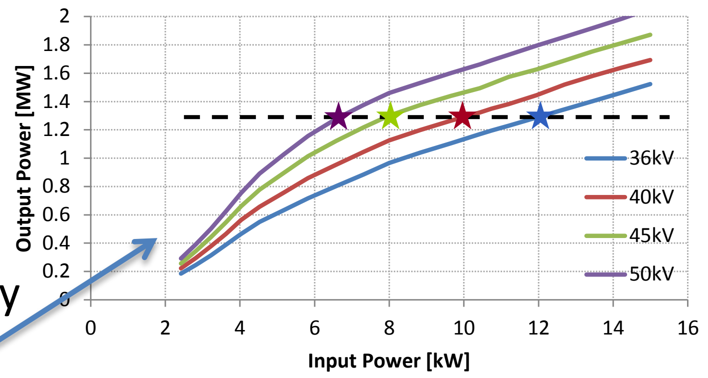
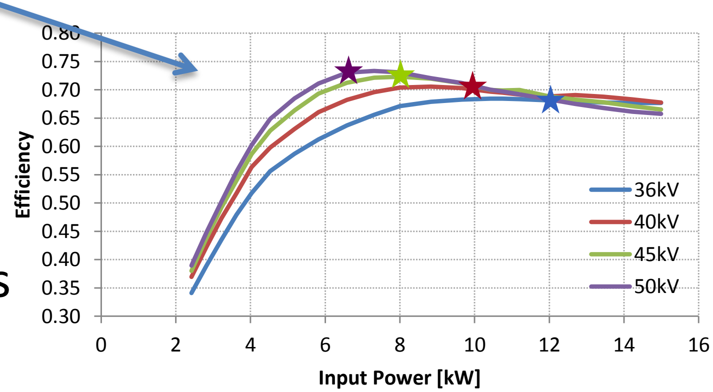
Operational Optimisations
Courtesy of L3 Communications



1.3 MW
70% eff

Power and Efficiency Impact of HV

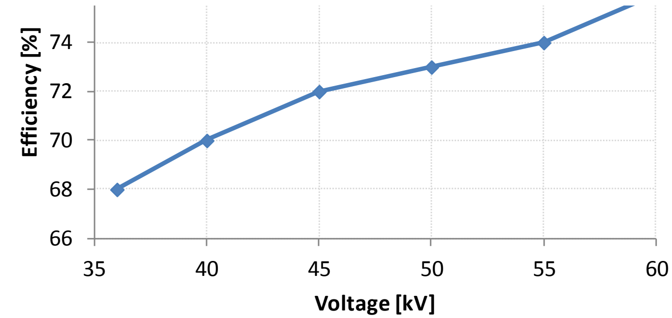




Increased beam voltage provides for better performance

- Increases gain
- Increases efficiency
- Decreases body current

Simulations are for 10 beams



MAGIC Prediction of MB-IOT Performance Courtesy of Thales and CPI

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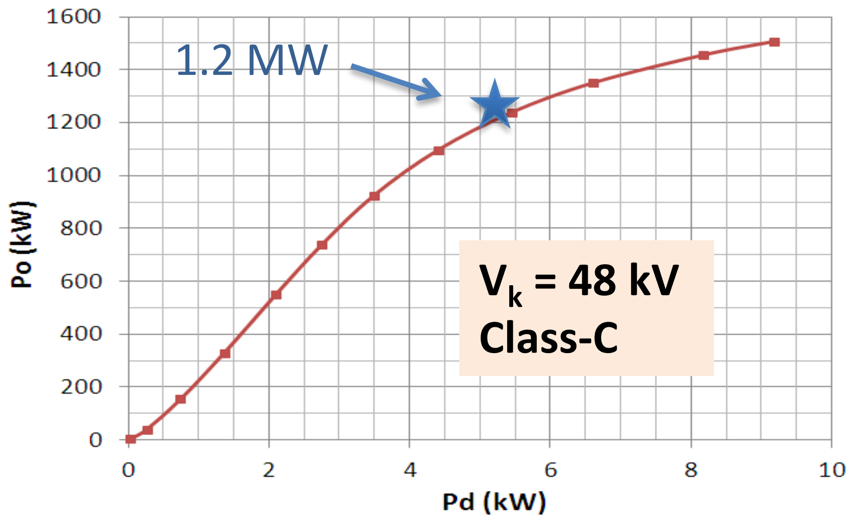
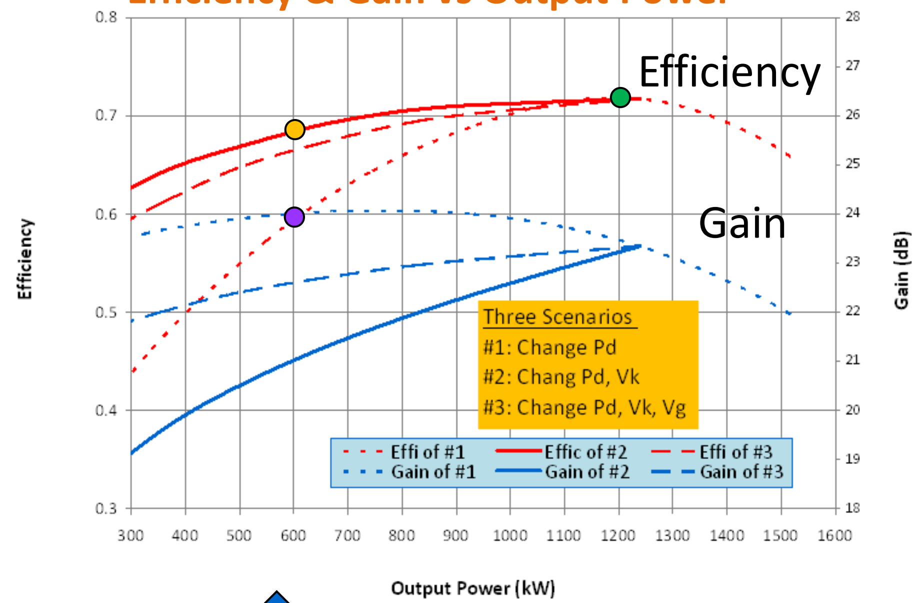
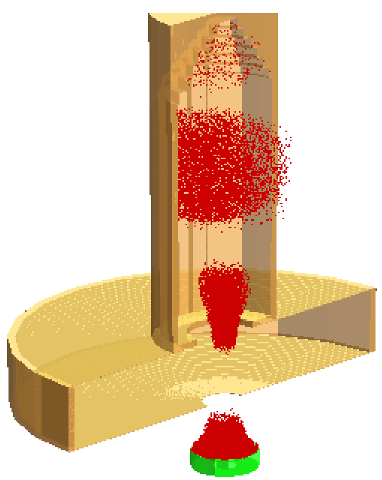
Power Transfer Curve



Efficiency & Gain vs Output Power





MAGIC-3D simulation of one beam with MB-IOT off-axis B-field

- At 1.2 MW, η = 72% with V_k = 48 kV
- At 600 kW
  - η = 59% with V_k = 48 kV
  - η = 68% with V_k = 34 kV

CPI THALES

Future Prospects

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ESS requires 1.2 MW plus overhead

- Short development time available
- Preference for low voltage
- ‘Proven’ technology
- Factor of 10 up in power

Future machines require:

- More power another factor of 10?
- Better efficiency
- Better reliability
- Smaller footprint, etc

Combined amplifier and accelerating cavity structures ★

High current emission cathodes ★

Optical emission cathodes for ultra high repetition rate

Energy recovery / Depressed collectors

Grid controlled emission with bunch forming cavities ★

High voltage, 1 MW, single cathode

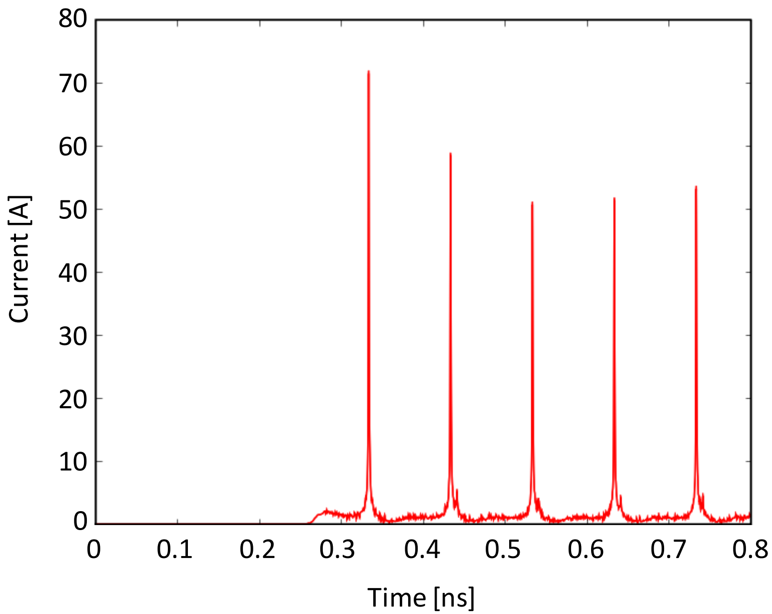
Double grid devices and current manipulation for bunch shortening

- Efficiency, higher frequency

10 MW MBIOT by combination of 1 MW tubes

Short Bunch Length for High Efficiency Courtesy of L3 Communications

- L-3 developed a novel technique for very short pulse generation
- Bunch is formed, then accelerated to high voltage
- Electrons arrive at the output cavity over a very small portion of the RF cycle, with very small energy spread



- Simulation performed with MICHELLE-TD of a IOT-type gun designed to produce short bunches
- FWHM of electron bunch is 3.6 degrees of RF cycle

L3 communications

Acknowledgements

Special thanks to

Thales, CPI and L3 for agreeing to publish some of the design details, calculations and predictions