High Power IOTs

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The Inductive Output Tube

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

- To overcome limitation of output power and efficiency by grid and anode interception
- The energy of the electron beam is extracted trough a resonant cavity
- Achieved: 100 W at 450 MHz, 10 dB power gain and 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

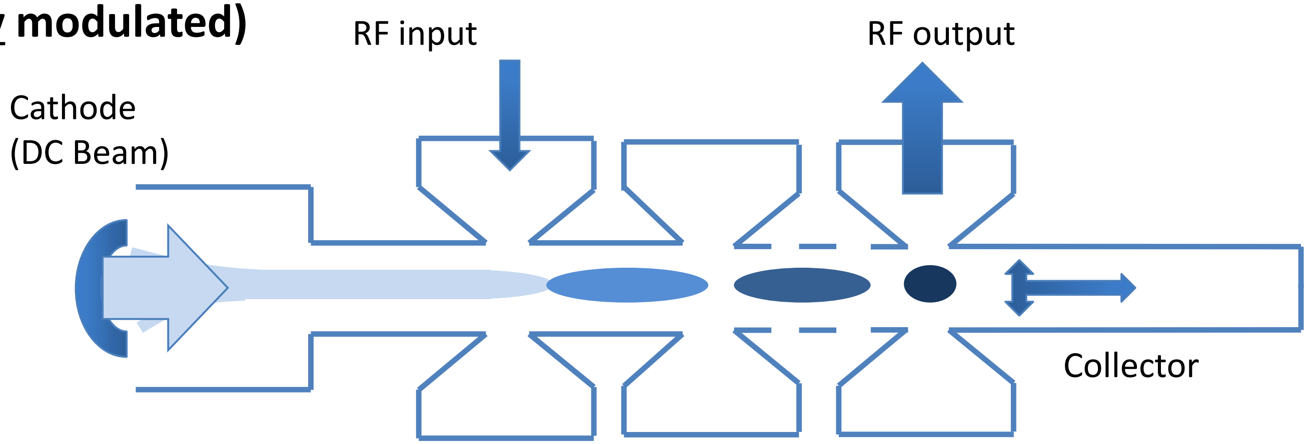
- Intense competition with velocity modulated tubes (klystron had just been invented by the Varian brothers)
- Difficult to manufacture
- Low gain

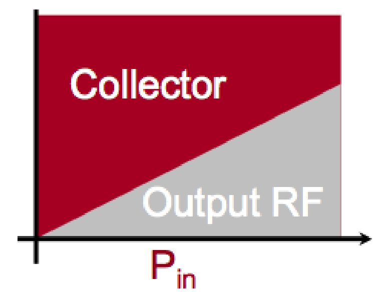
The IOT is often described as a cross between a klystron and a triode hence Eimac's trade name 'Klystrode'

The Main Principles

Klystron

(<u>Velocity</u> modulated)



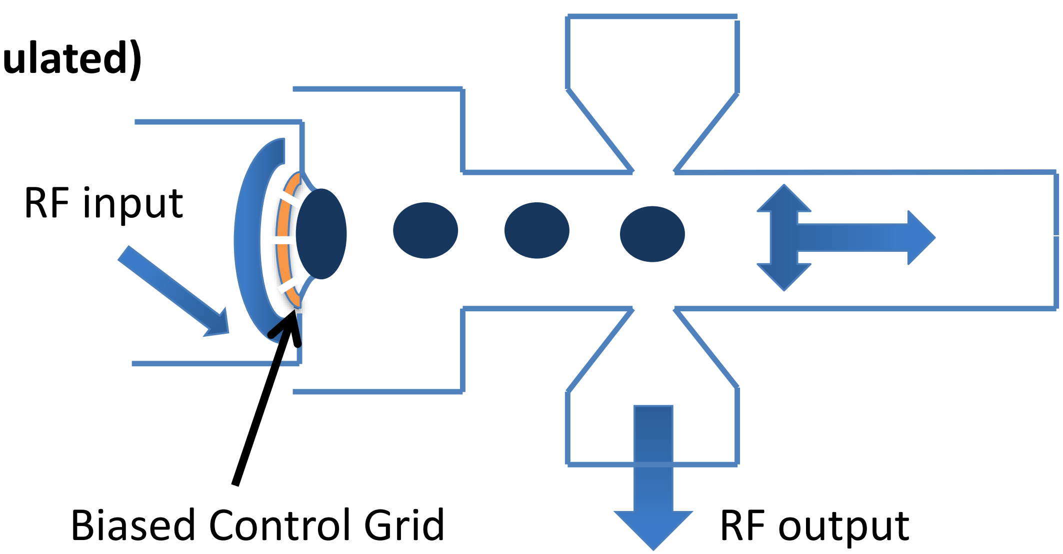


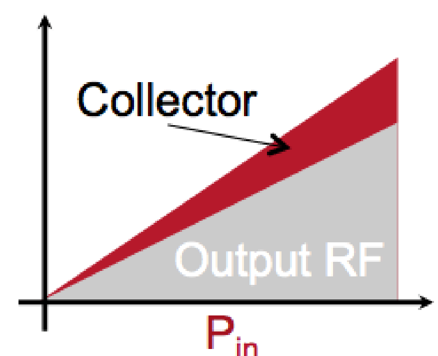
$$I_0 = P(V_0)^{3/2}$$

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

IOT

(<u>Density</u> modulated)





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

IOTs highlights

- The current also depends on the grid voltage.

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

- ✓ High efficiency at point of operation
- ✓ Efficiency drops slowly at reduced output power
- ✓ Good Linearity

- Because there is no velocity modulation, extraction efficiency can be high (small velocity spread in the beam): 70-75% are typical values
- The device is short, so pushing factor is small
- Collector only ever handles spent RF beam (e.g. at Eff. 50% P_{Coll} = RF power)

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

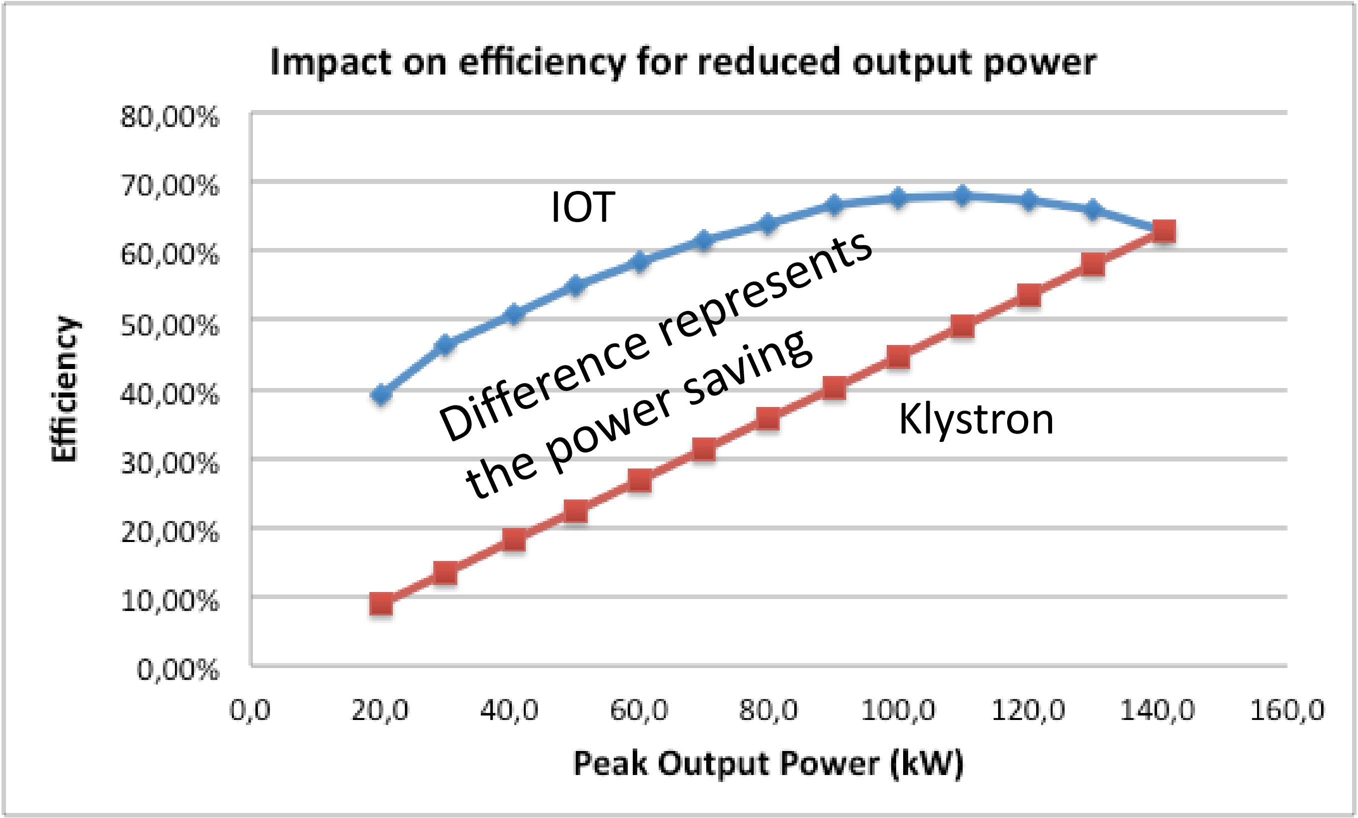
- varying power loads
- Non uniform power profiles
- Margins for overhead for regulation
- One-to-one relationship with amplifier to accelerating structure

Proton Linacs in particular can benefit and circulating machines with high regulation requirements

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 is limited to about 1.3 GHz

Efficiency comparison of Klystrons and IOTs



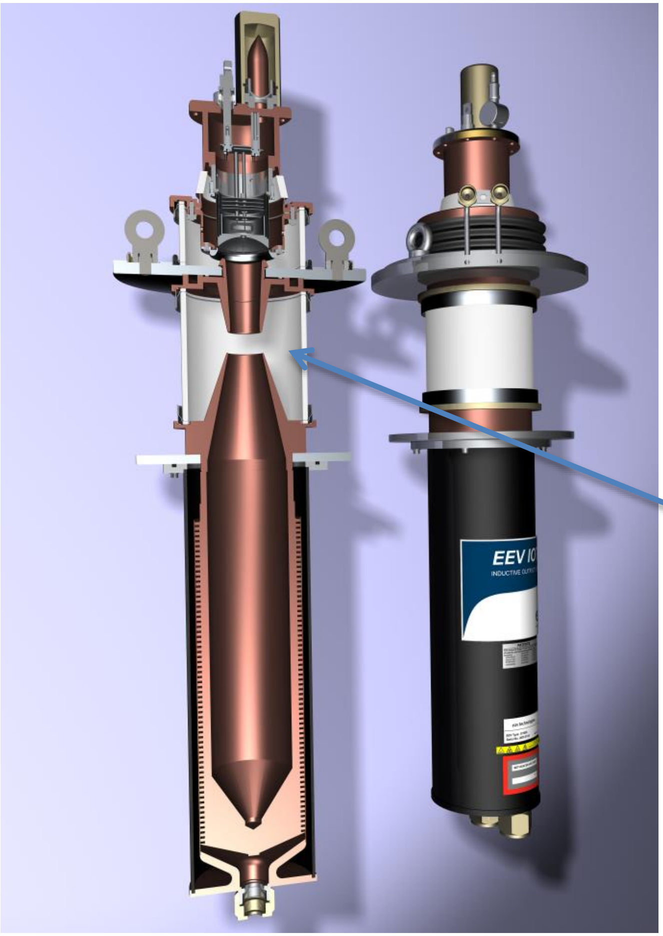
IOT measurements courtesy of M. Boyle, L3

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

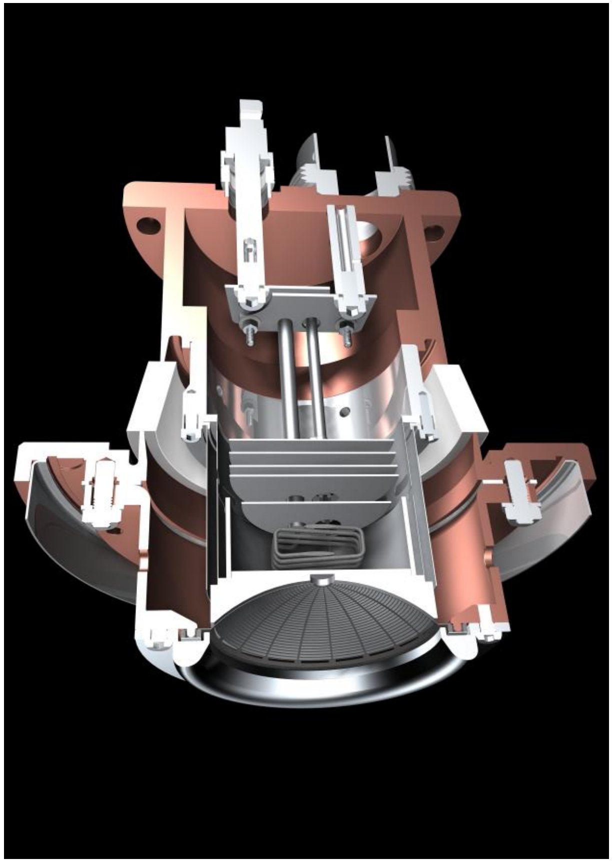
- Klystron assumed to have same saturated efficiency as the IOT
- No optimisation of coupling, voltages, perveance for different power levels

Typical Broadcast IOT

Courtesy of e2v



Output ceramic. External output cavity is not shown



Cathode-grid assembly

Selection of facilities using IOTs

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

diamond

CERN
800 MHz
60 kW
Thales IOT

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

ALBA
Synchrotron Light Facility

NSLS II (BNL)
L3 IOT, 500 MHz
80 kW CW

Elettra
500 MHz
150 kW IOT based amplifier for Combination of 2x80 kW Thales - E2V

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

Other IOT technology

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IOTs designed for various applications

But series production has been < 100 kW

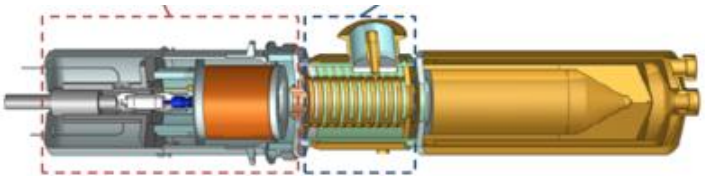
Communications & Power Industries

microwave power products division

267 MHz

300 kW CW

Depressed collector IOTs

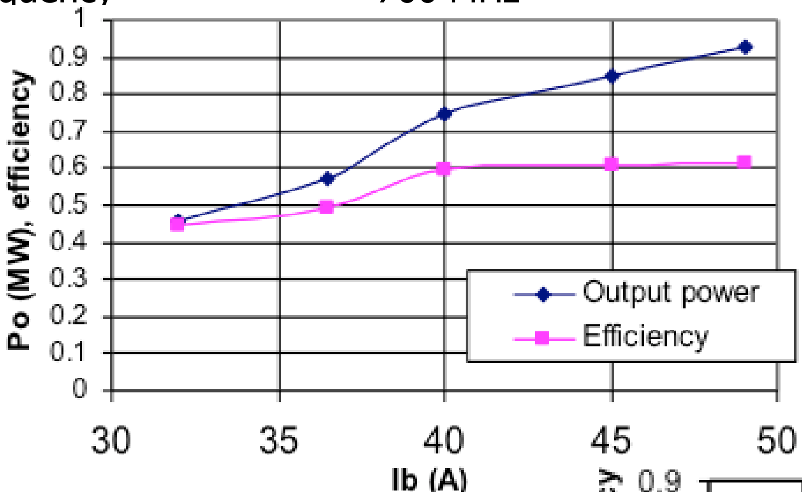


L3 wide band IOT

700 MHz HOM IOT Experience

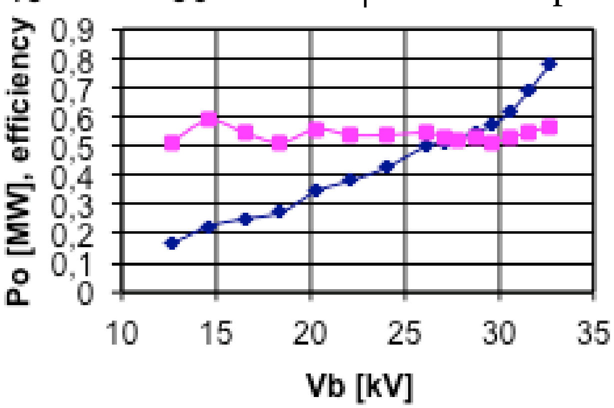
Commissioned from Los Alamost NL to CPI for the APT proton accelerator

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



Test Results
(pulsed)

The APT project was abandoned in 1999 and with it the idea of a super-power IOT…..



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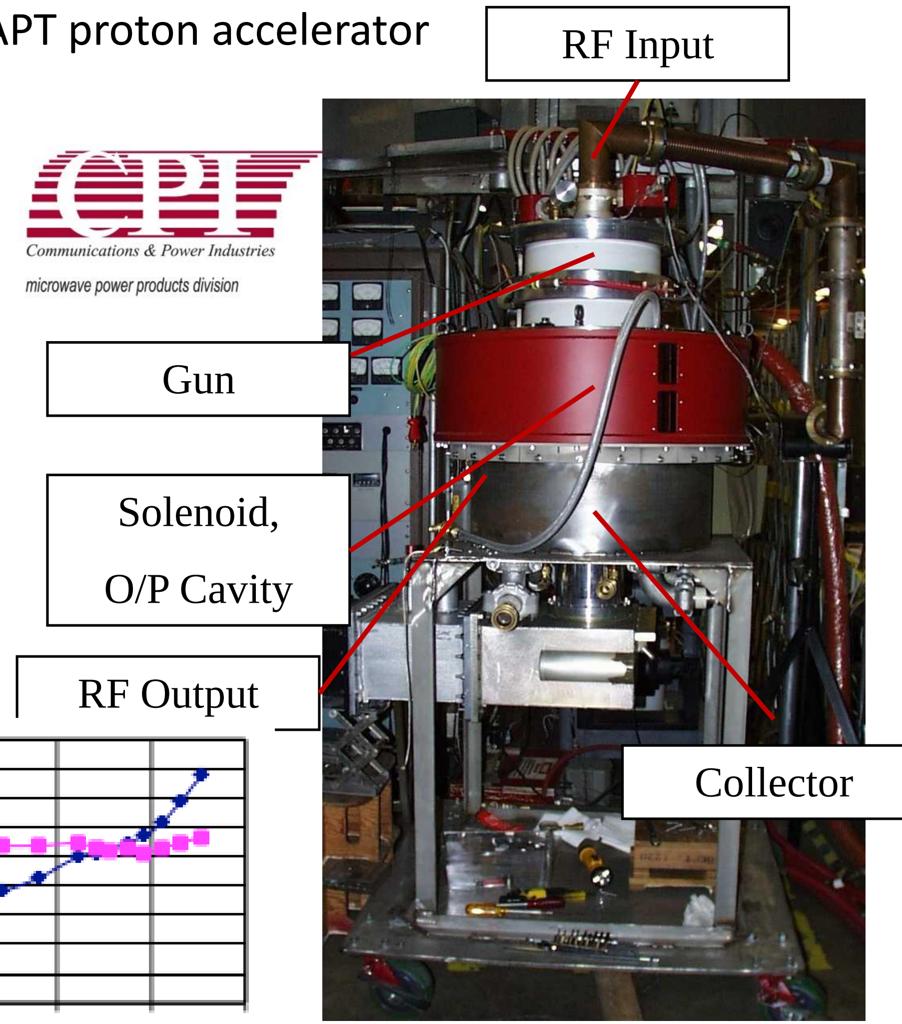


VHP-8330A IOT

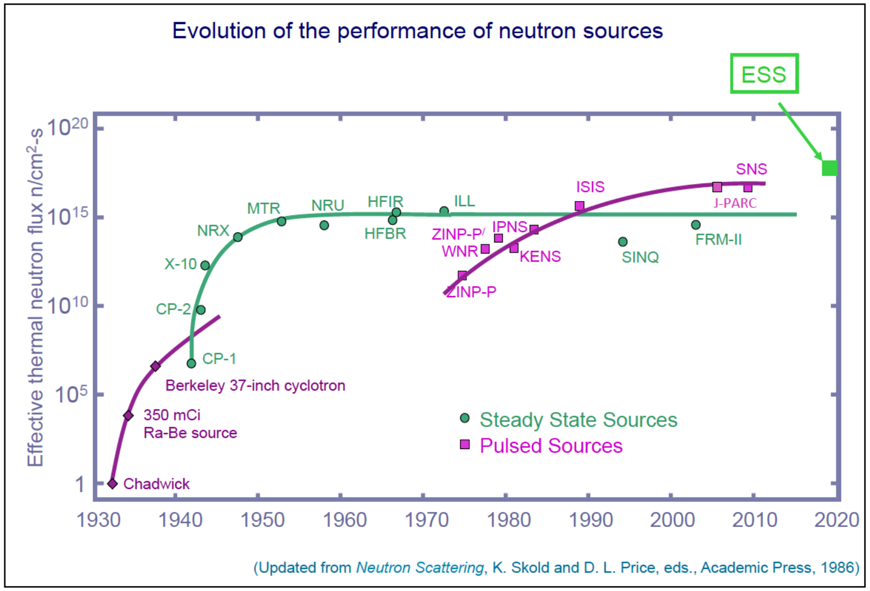
The ESS project

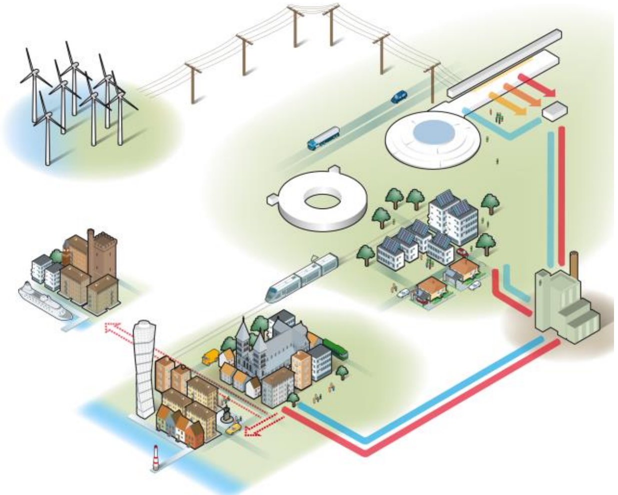
EUROPEAN SPALLATION SOURCE

- ESS is a neutron spallation source for neutron scattering measurements.
- The neutrons are produced by a 2 GeV proton beam impacting on a tungsten target.
- The proton linac will be the most powerful ever built and it will require over 150 RF sources.

ESS **accelerator** parameters:

Average beam power: 5 MW
Pulse length: 2.86 ms
Peak beam power: 125 MW
Pulse repetition rate: 14 Hz
Proton energy: 2 GeV
Peak beam current: 62.5 mA
High availability: >95%
Flexible design for a future power upgrade





ESS will be a "green" facility: this means that it must guarantee at the same time:

- Machine reliability
- **Energy efficiency**

The ESS accelerator

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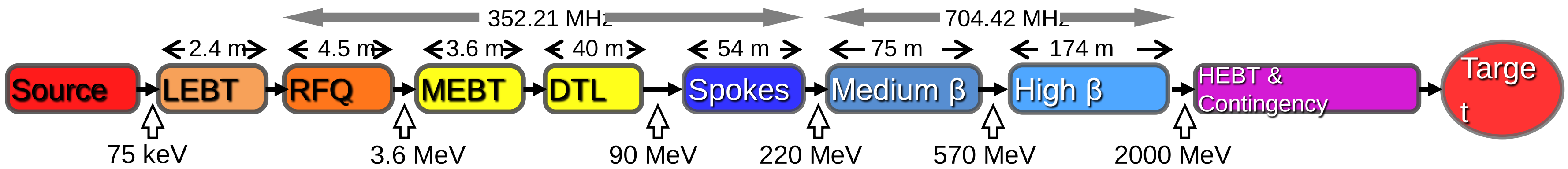
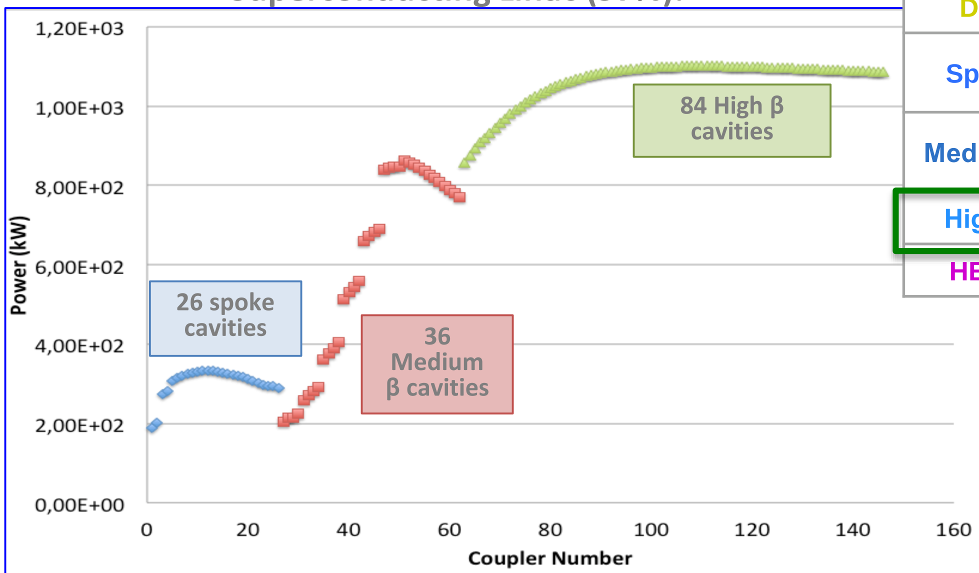


Normal-conducting Linac:

1 RFQ: 1.6 MW at 352 MHz required in input + 30% (overhead + losses);

5 DTL tanks (2 couplers/DTL): 2.2 MW at 352 MHz required in input + 30% (overhead + losses);

Superconducting Linac (97%):



	Energy (MeV)	Frequency (MHz)	No. of Cavities	βg	Temp (°K)	RF power (kW)
Source	0.075	-	0	–	~300	–
LEBT	0.075	-	0	–	~300	–
RFQ	3.6	352.21	1	–	~300	1600**
MEBT	3.6	352.21	3	–	~300	20**
DTL	90	352.21	5	–	~300	2200**
Spoke	220	352.21	26 (2/CM)	0.5 β_{opt}	~2	330**
Medium β	570	704.42	36 (4/CM)	0.67	~2	870**
High β	2000	**704.42**	**84** (4/CM)	0.86	~2	**1100****
HEBT	2000	–	0	–	~300	–

Total High Power RF: 133 MW peak (4% duty) plus overhead
90 MW to High Beta Section!

** Plus overhead for control

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

- 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

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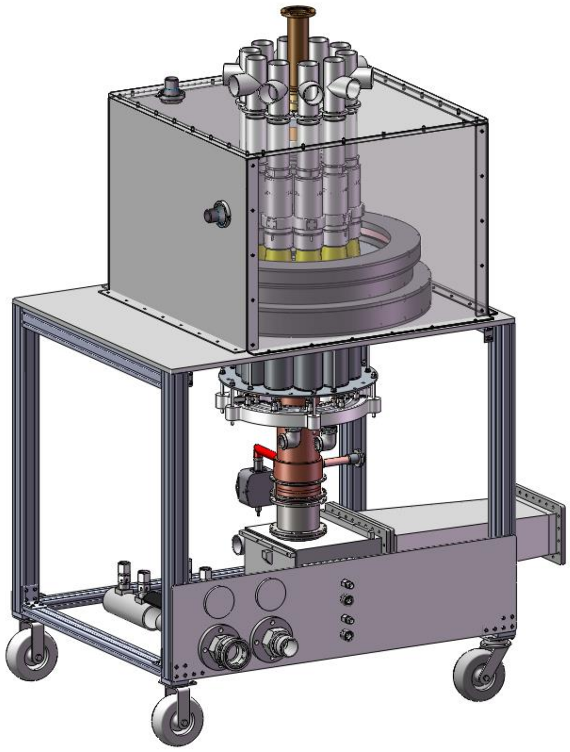
Multi-Beam IOT
10 beams
1.2 MW
704.42 MHz



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L3
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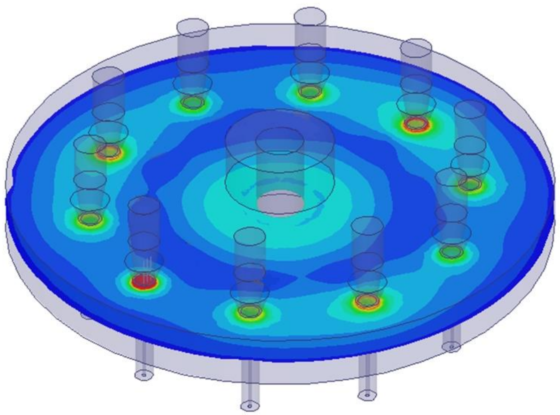
Output Cavity and DC Beam Studies Courtesy of L3 Communications

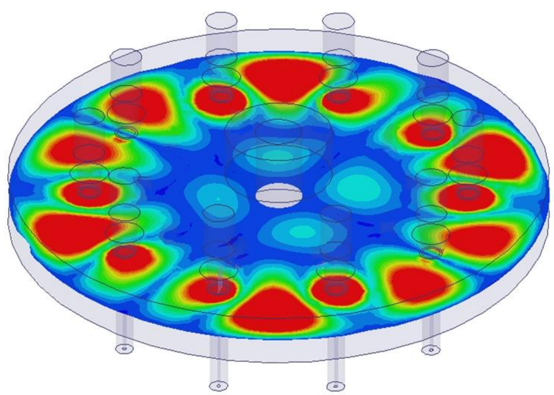
- Ten beams on a single bolt circle
- Output cavity supports a large number of modes
- HFSS used to map modes near harmonics of the drive frequency

Fundamental



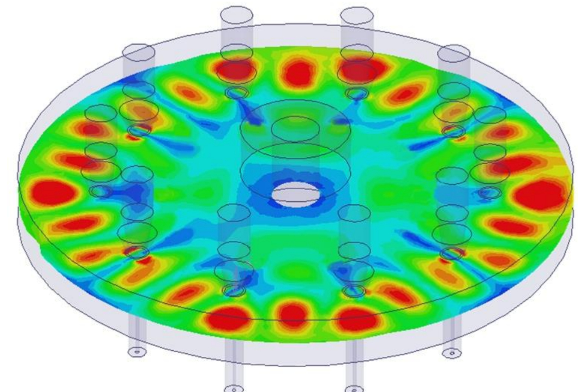
$TM_{1,0,0}$ at 704 MHz

Near Second Harmonic

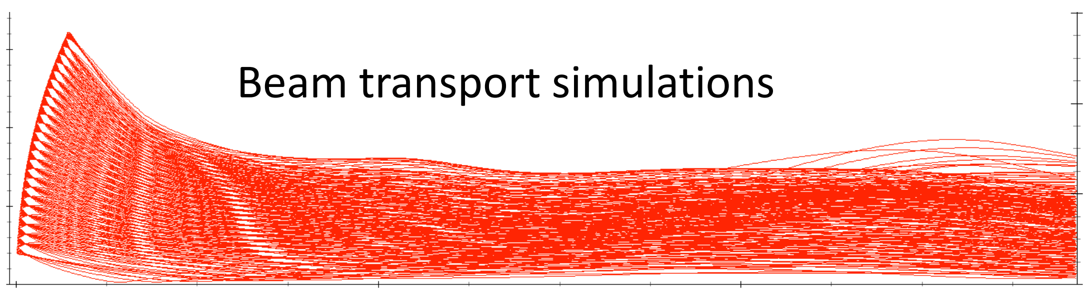


$TM_{1,16,0}$ at 1417 MHz

Near Third Harmonic



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



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Beam transport and RF Interactions Courtesy of L3 Communications

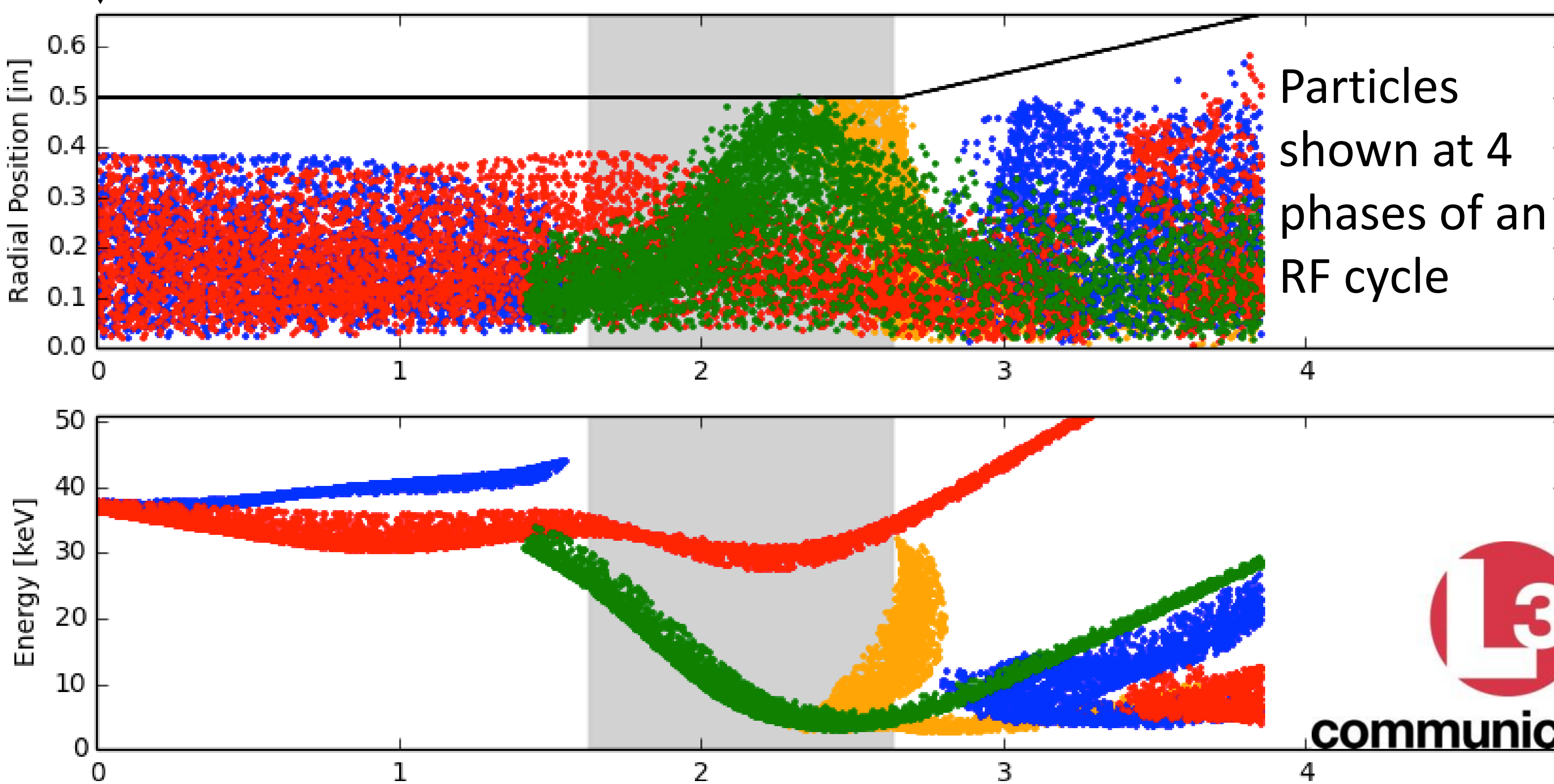
Beam profile imported here

Propagated in the presence of the magnetic field imported from Maxwell

Drift tunnel

Output Gap

Drift tunnel taper



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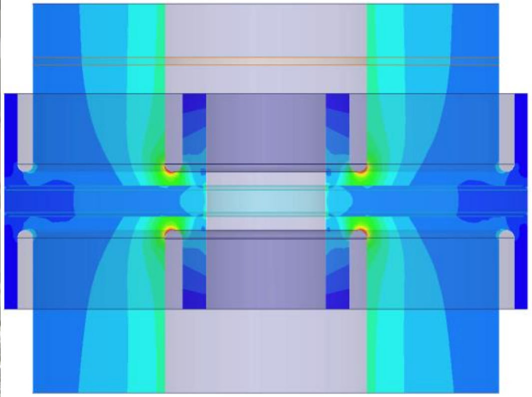
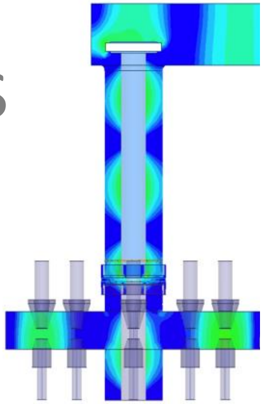
RF Output Circuit and Output Window Courtesy of L3 Communications

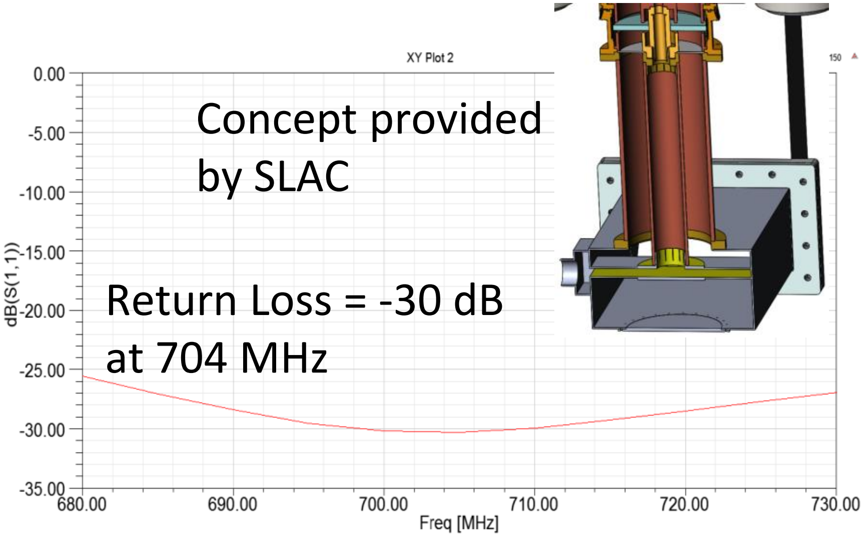
- Air cooled SLAC design Coaxial window from B-factory klystron
  - 1.2 MW CW operation, 476 MHz
  - TiN coated and has modest peak electric field



SLAC Proprietary

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





Operational Optimisations
Courtesy of L3 Communications

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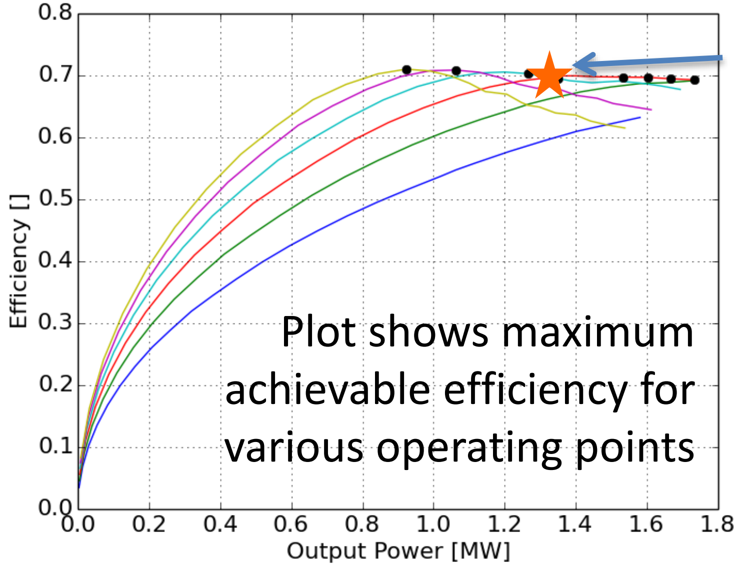
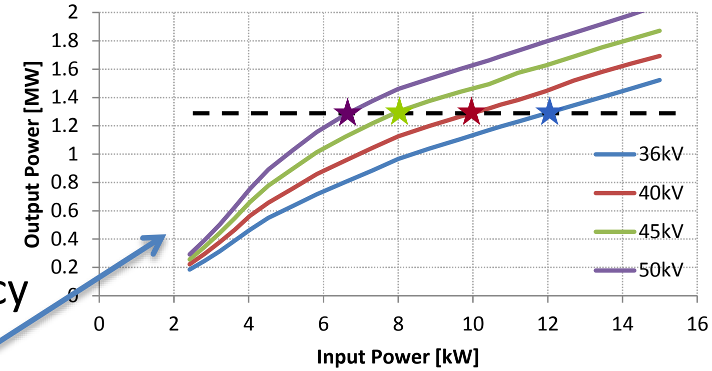
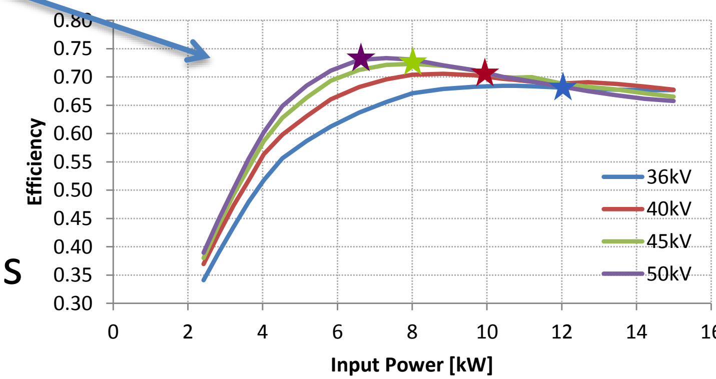


1.3 MW
Efficiency=70%

Plot shows maximum achievable efficiency for various operating points

Power and Efficiency Impact of HV

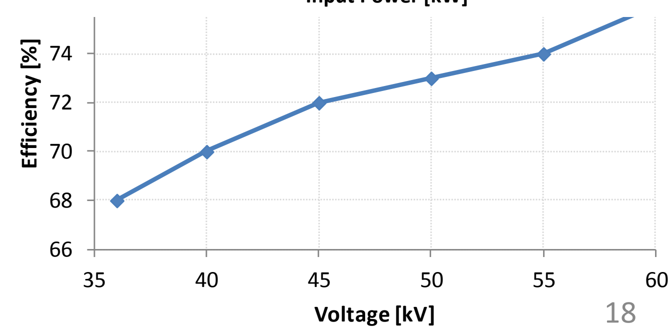




Increased beam voltage provides for better performance

- Increases gain
- Increases efficiency
- Decreases body current

Simulations are for 10 beams



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

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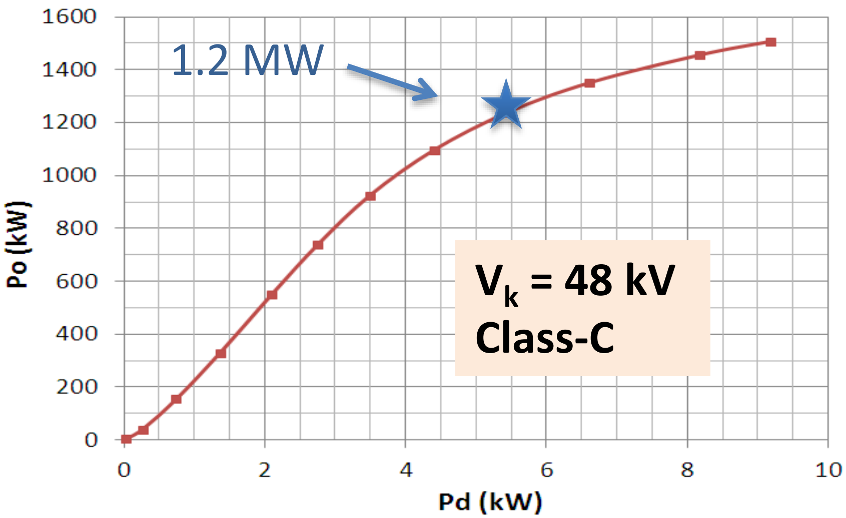
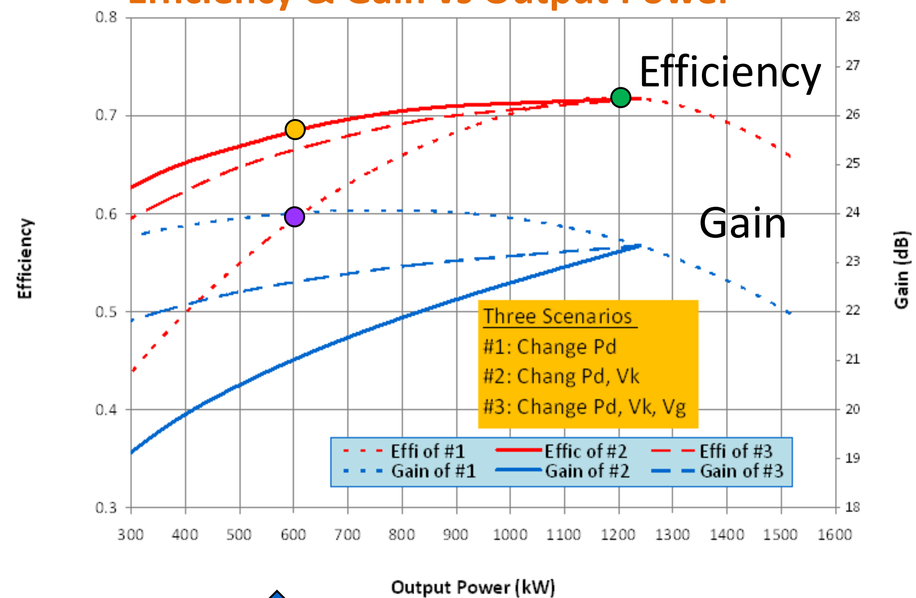
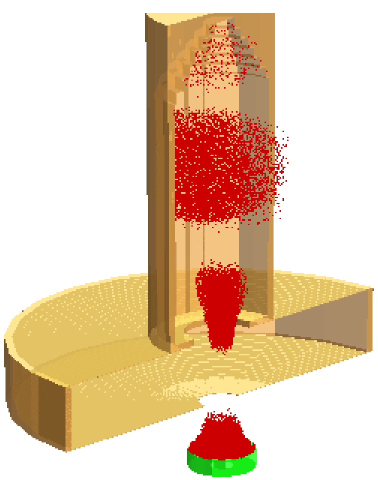
Power Transfer Curve



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

Conclusions and Future Prospects

ESS requires 1.2 MW plus overhead:

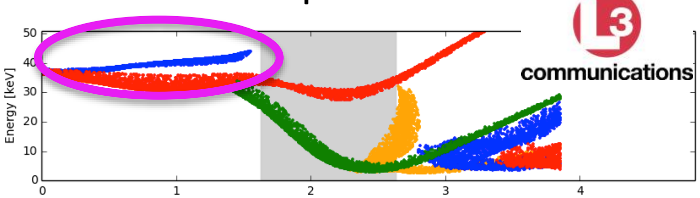
- Short development time available
- Preference for low voltage
- 'Proven' technology
- Factor of 10 up in power

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

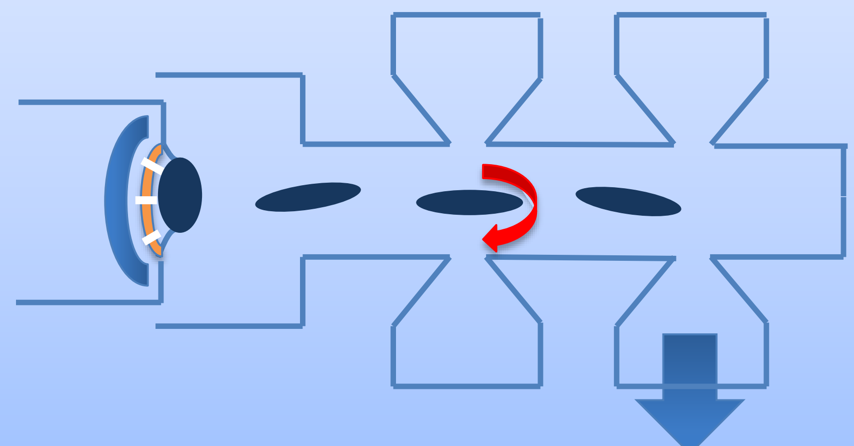
What else could we achieve?

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

Example:
MBIOT development for ESS



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



Acknowledgements

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