The MB-IOT Developments for ESS

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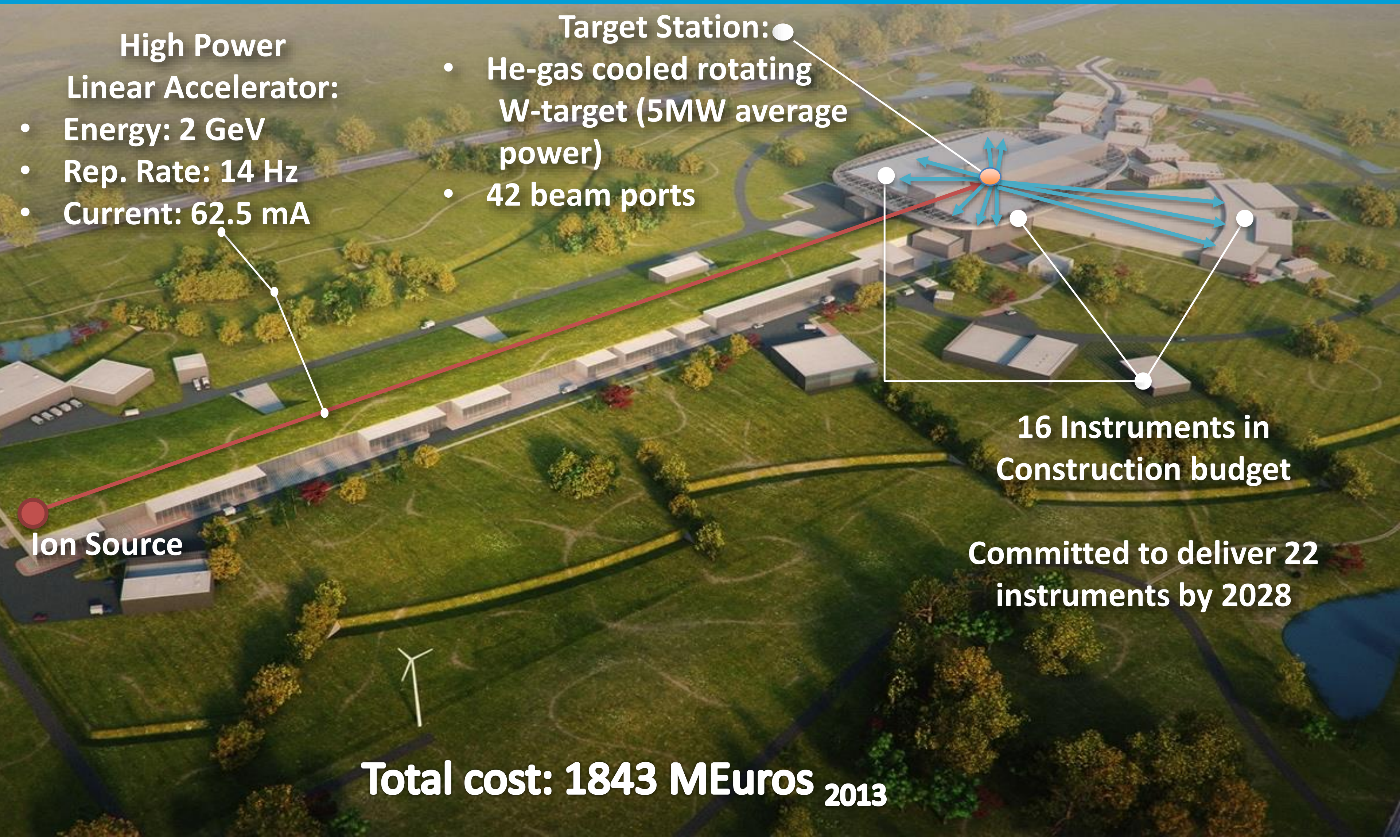
ESS design

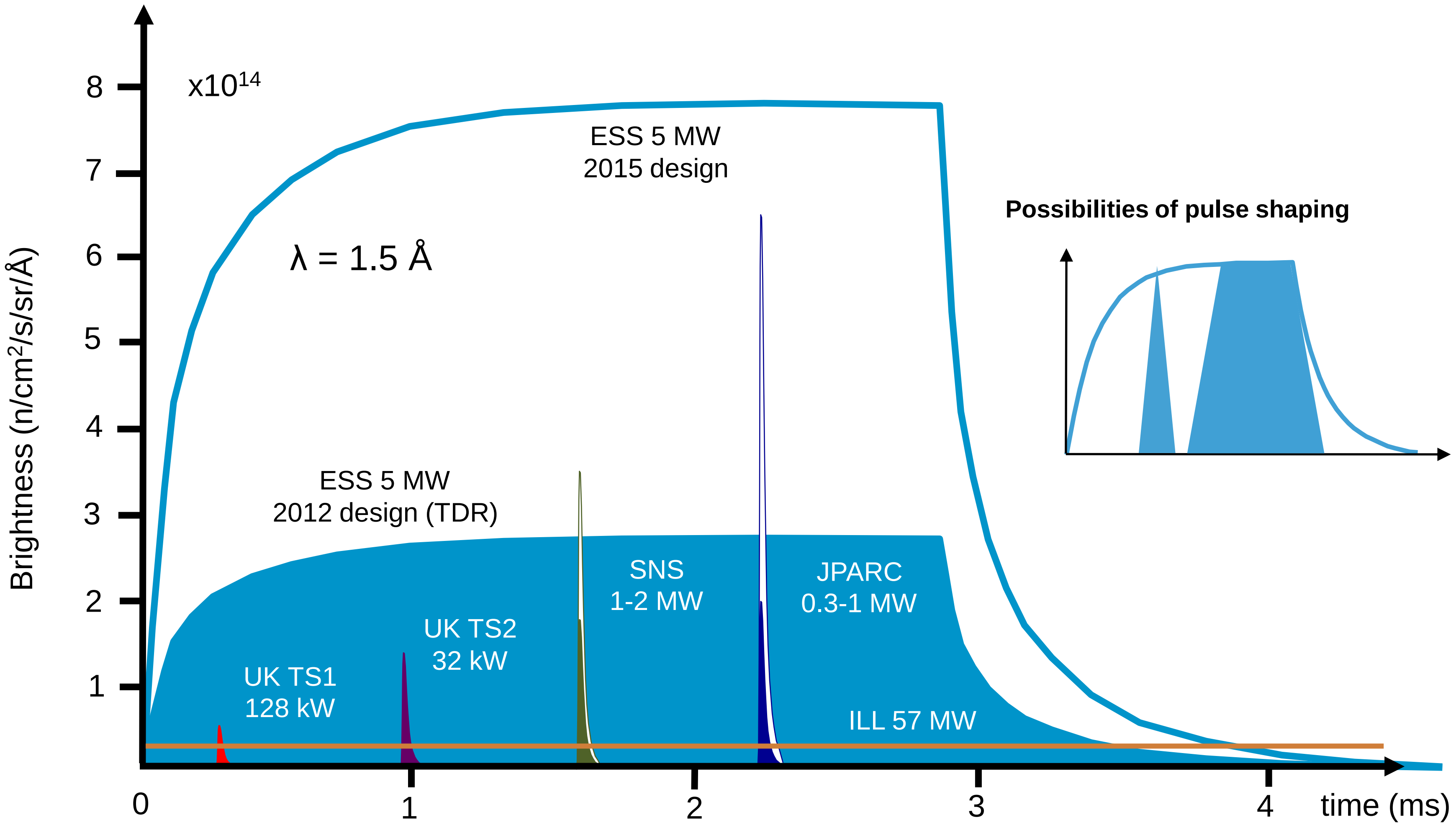


High Power
Linear Accelerator:
• Energy: 2 GeV
• Rep. Rate: 14 Hz
• Current: 62.5 mA
Target Station:
• He-gas cooled rotating W-target (5MW average power)
• 42 beam ports
16 Instruments in Construction budget
Committed to deliver 22 instruments by 2028
Ion Source
Total cost: 1843 MEuros 2013

Progress on civil construction

27 April 2016

Long-pulse performance



RF Power Requirement

Design Drivers:

Average Beam Power 5 MW

Peak Beam Power 125 MW

High Availability

- First beam at 572 MeV in June 2019
- 5 MW capability for 2023

Key parameters:

-2.86 ms pulses

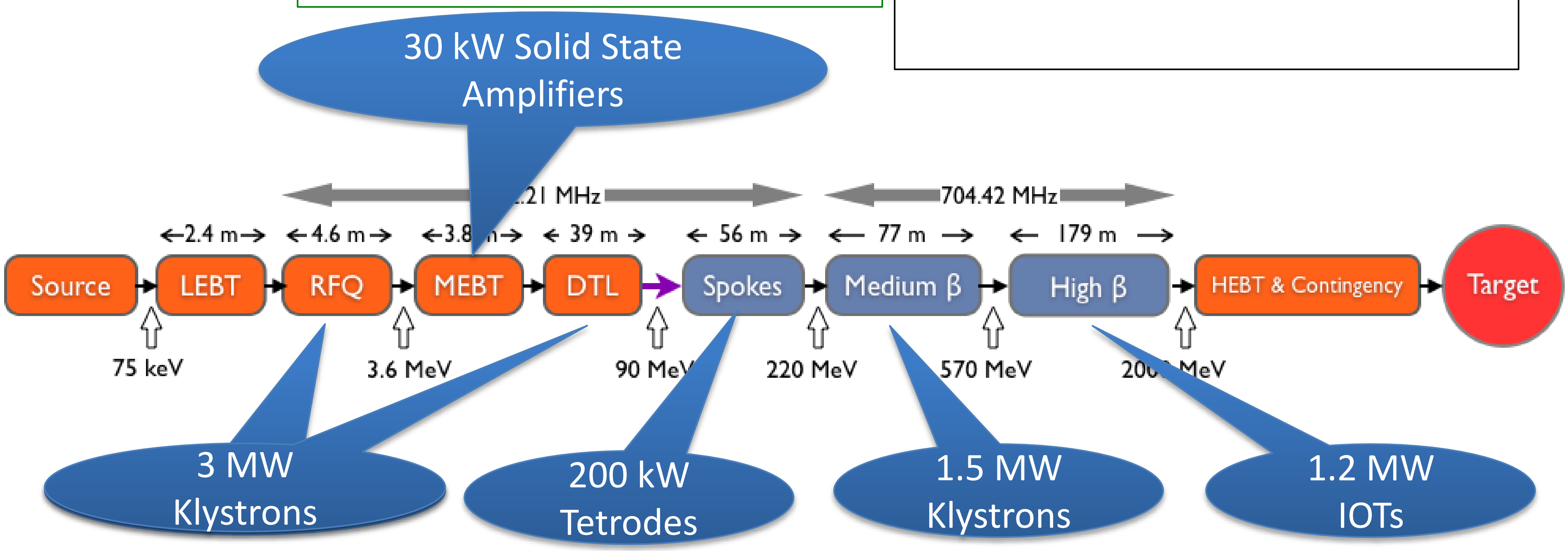
-2 GeV

-62.5 mA peak

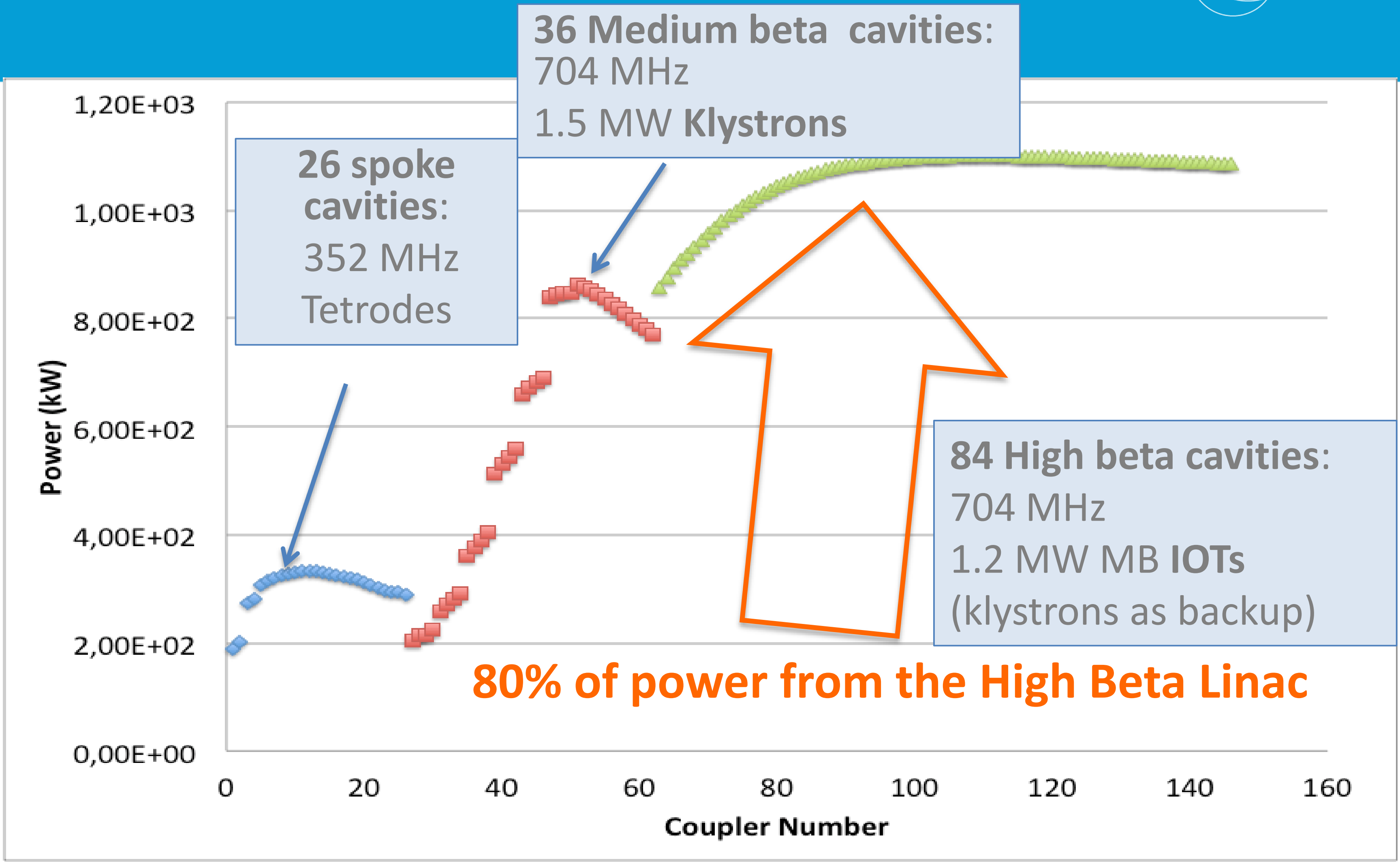
-14 Hz

-Minimize energy use

-Flexible design for mitigation and future upgrades



ESS accelerator power profile

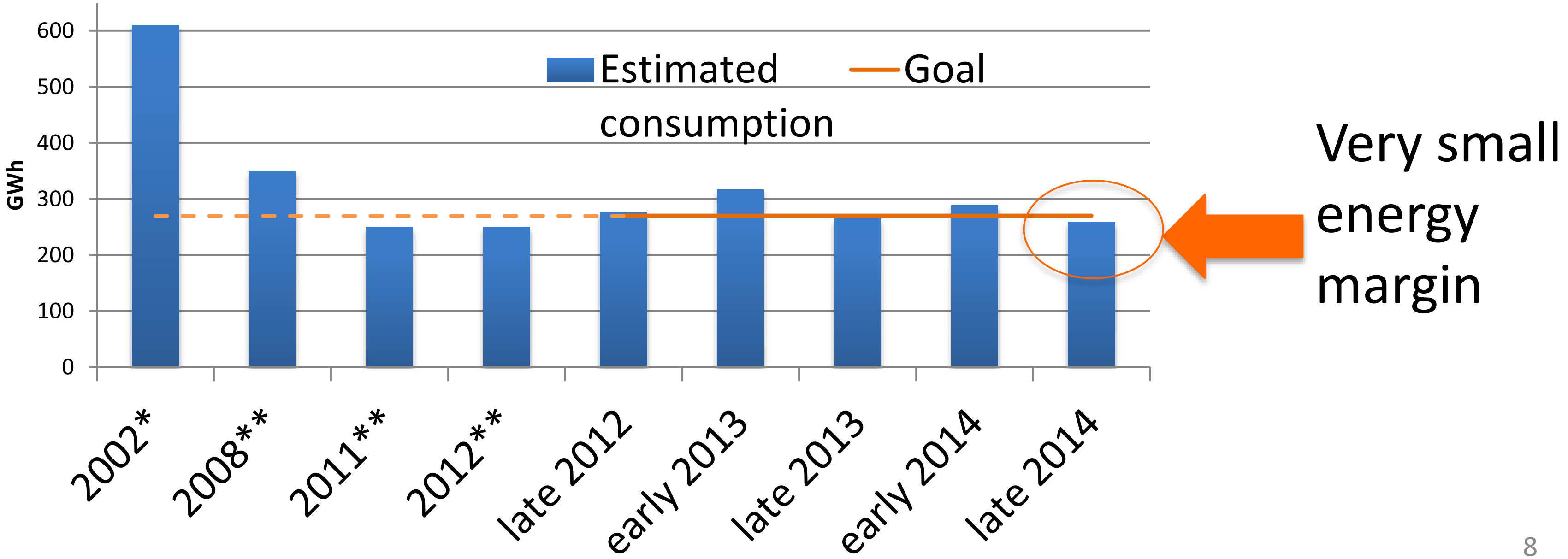


6 off 352 MHz klystrons 3 MW for RFQ and DTL tanks
3 off 352 MHz, 30 kW Solid state amplifiers for bunchers

ESS Energy Policy

Energy Goals:

- ***Responsible****: The energy efficiency of every aspect of operations will be carefully considered in the design phase …. ≤ 270 GWh at full operation.*
- ***Renewable:*** *All energy will be from renewable sources.*
- ***Recyclable****: All recuperated waste heat will be re-used.*



Efficiency and Power Consumption

Saturation efficiency

Gate efficiency

Power consumption

...

...

at the point of operation

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	

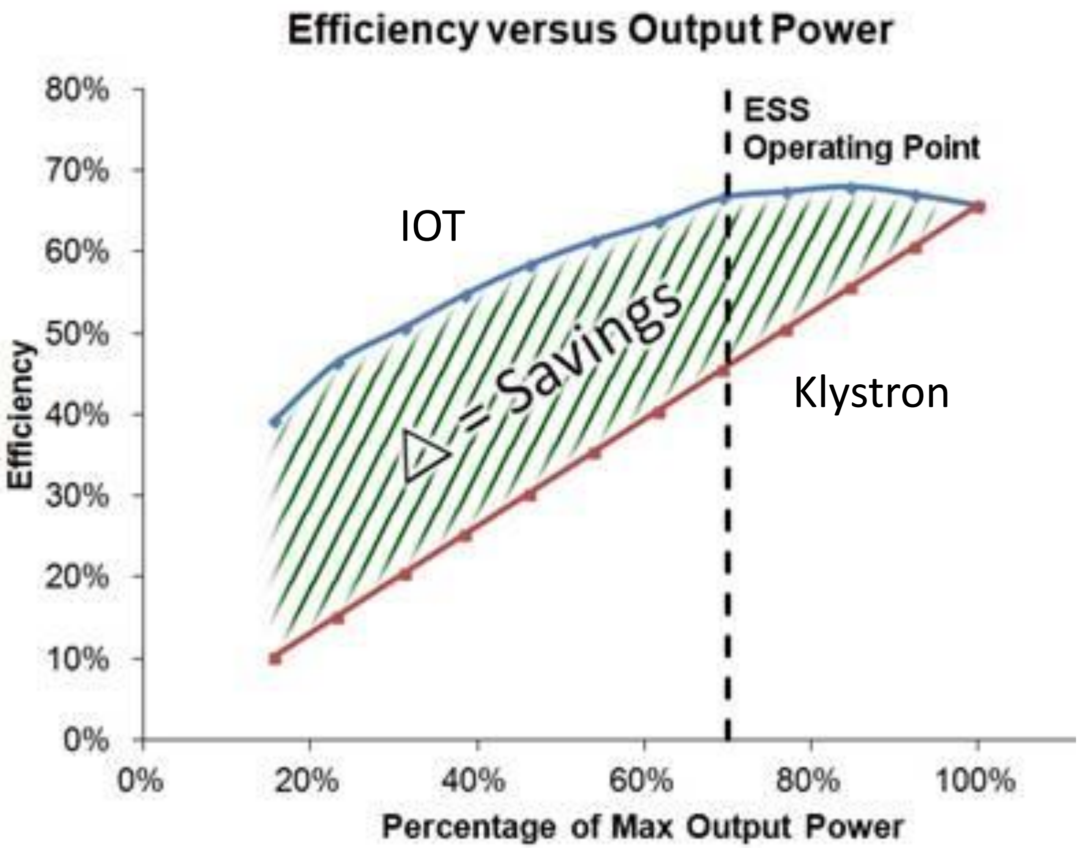
Work is being carried out in collaboration with CERN

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

3.3 MW power reduction by using IOTs for High Beta

Target: Approval for ESS series production in 2017/18

Efficiency comparison of traditional Klystrons and IOTs



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

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

Multi-Beam IOTs for ESS

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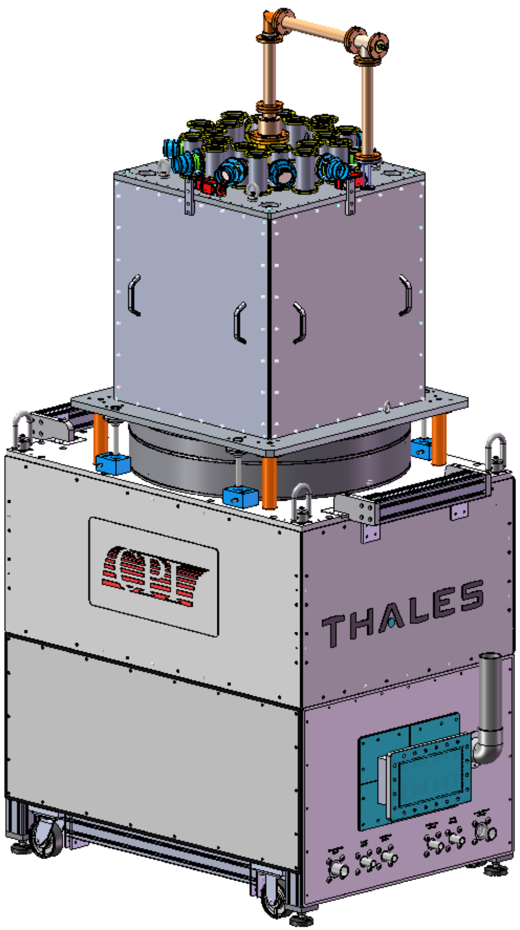


10 Beam Multi-Beam IOT
1.2 MW
704 MHz

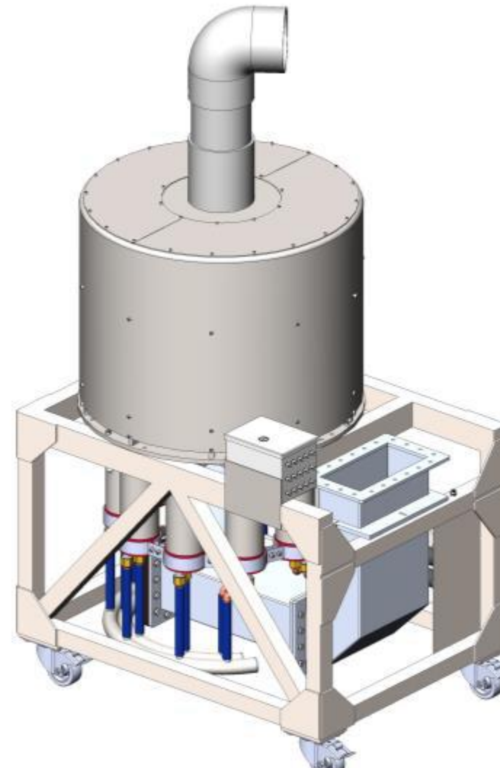
Two Contracts for **Technology Demonstrators**

- Thales/CPI Consortium
- L3

Contracts signed in September 2014

Project duration: 24 months

Testing at CERN

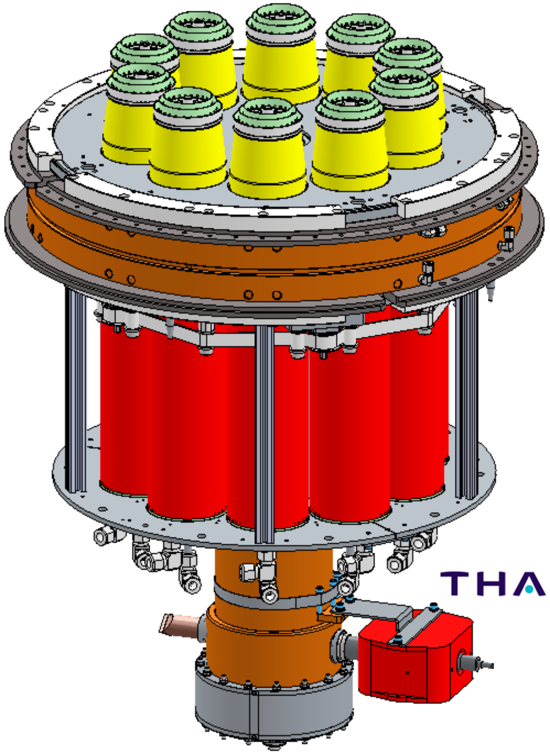


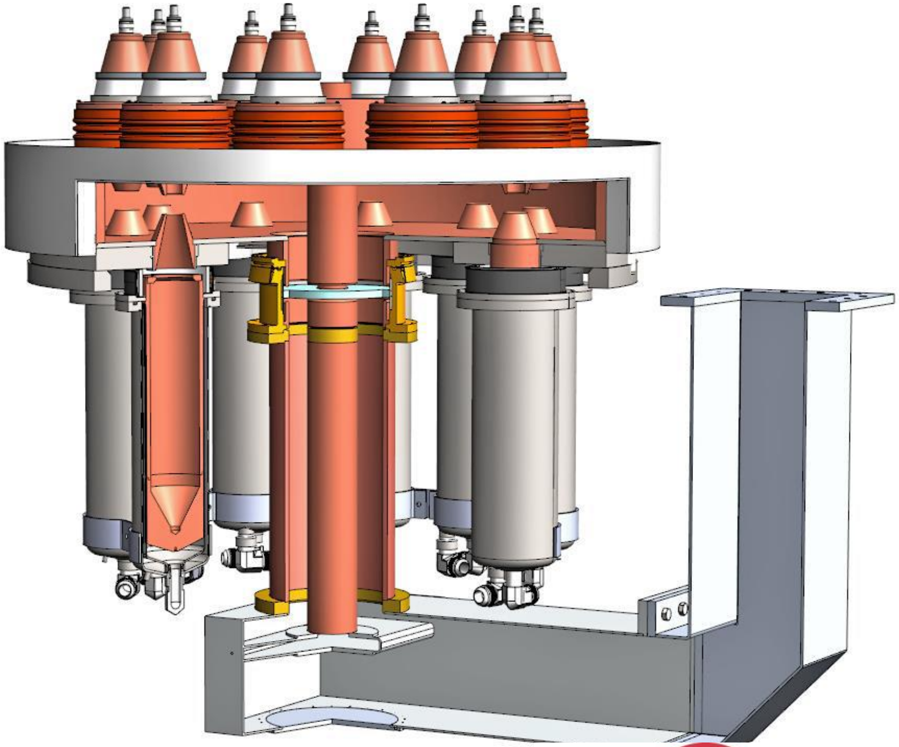
THALES

CPI Communications & Power Industries

microwave power products division

L3 communications





10 Beams placed on a bolt circle
Individual cathode and grid structures
Individual and isolated collectors
Single annular output cavity with one interaction gap per beam
Coaxial Output

Operational Optimisations
Courtesy of L3 Communications

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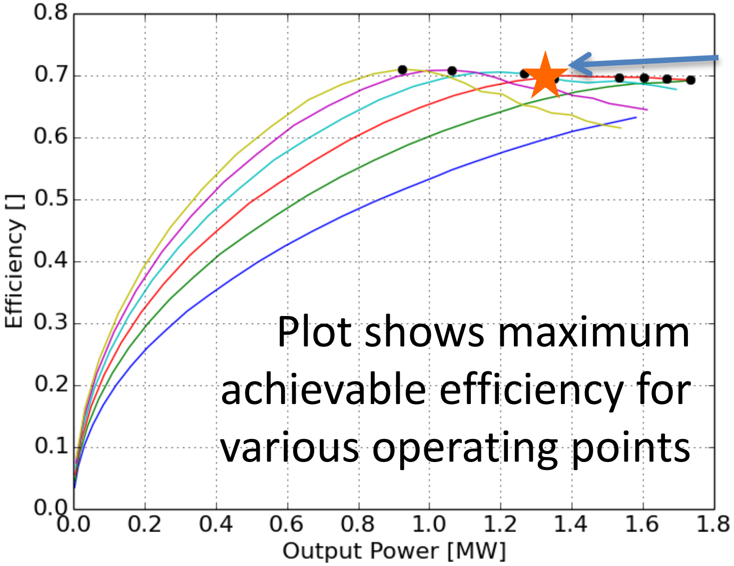
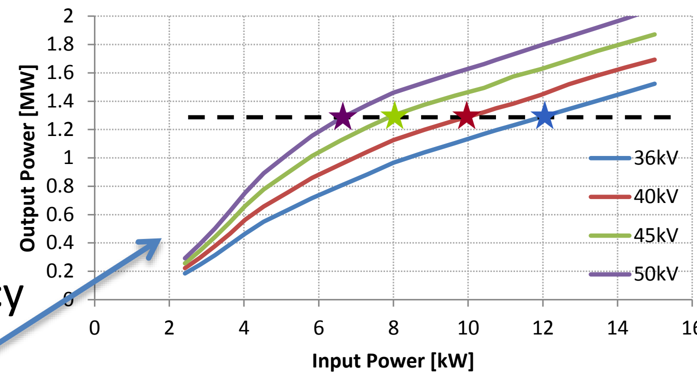
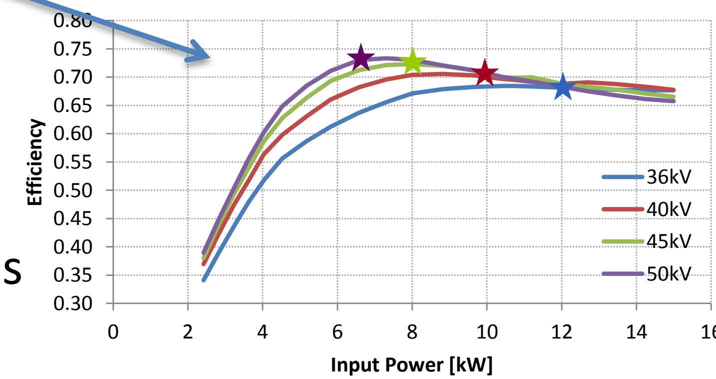


1.3 MW
70% eff

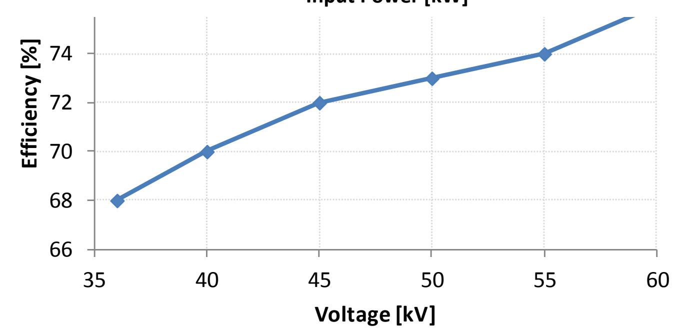
Power and Efficiency Impact of HV





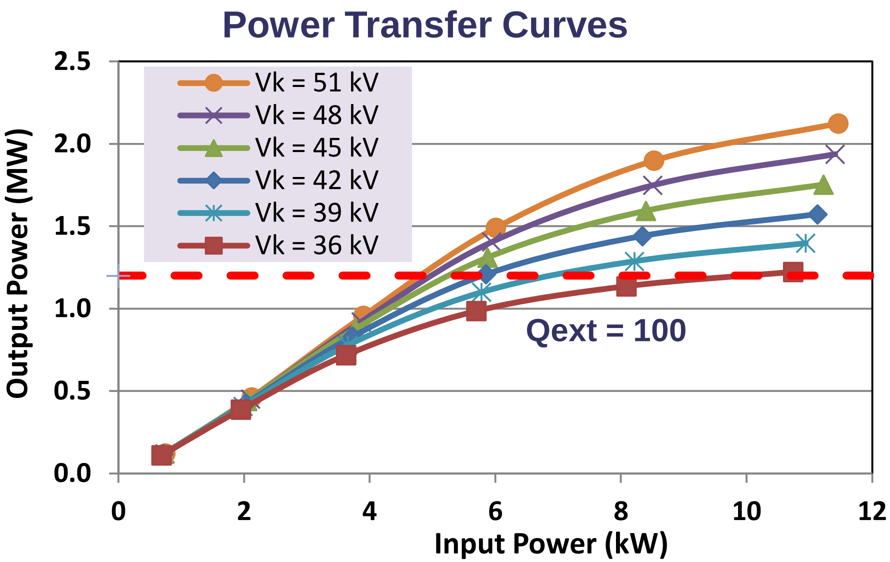
Increased beam voltage provides for better performance

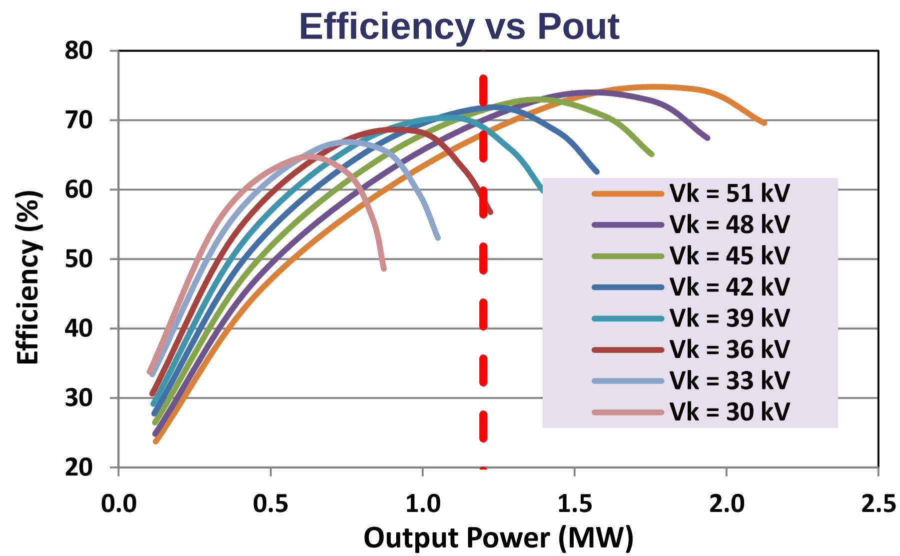
- Increases gain
- Increases efficiency
- Decreases body current



L3 communications

Operational Optimisations Courtesy of Thales and CPI



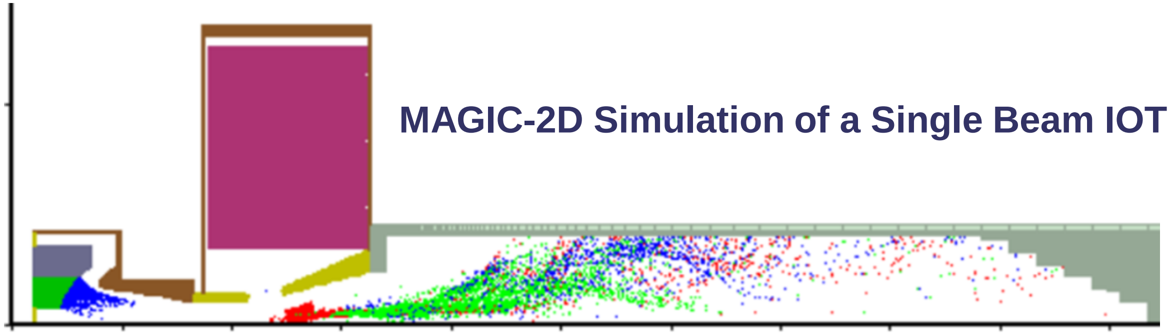


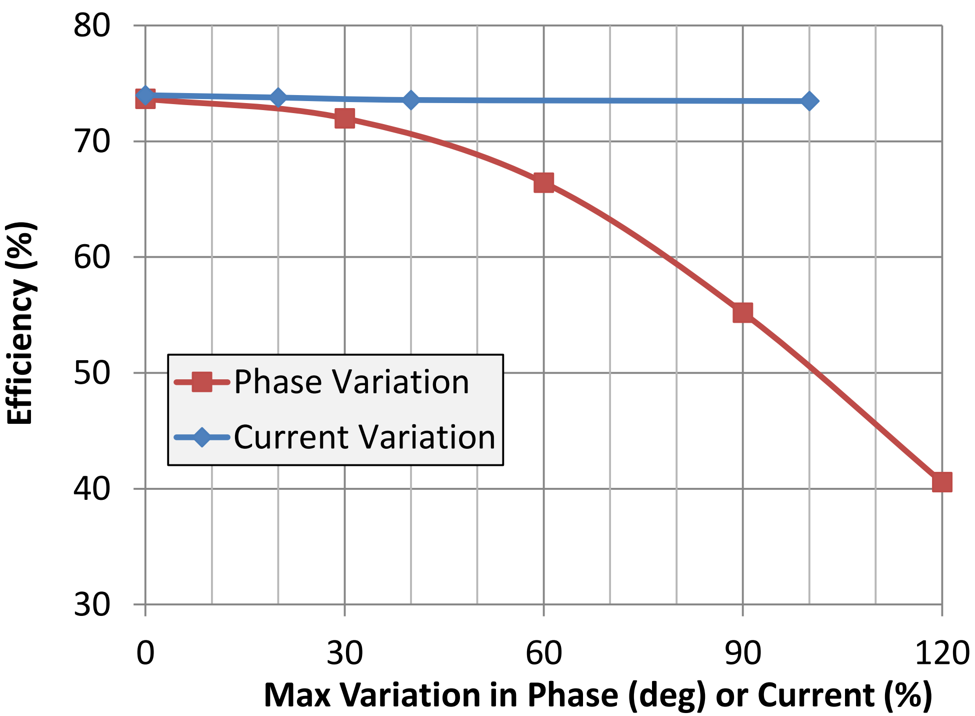
- **Predicted transfer curves for different beam voltages meet design targets of gain & efficiency**
- **High efficiency at reduced power**
- **-1dB bandwidth is 4.5 MHz (2 MHz requirement)**

Communications & Power Industries

microwave power products division

Operational Optimisations Courtesy of Thales and CPI

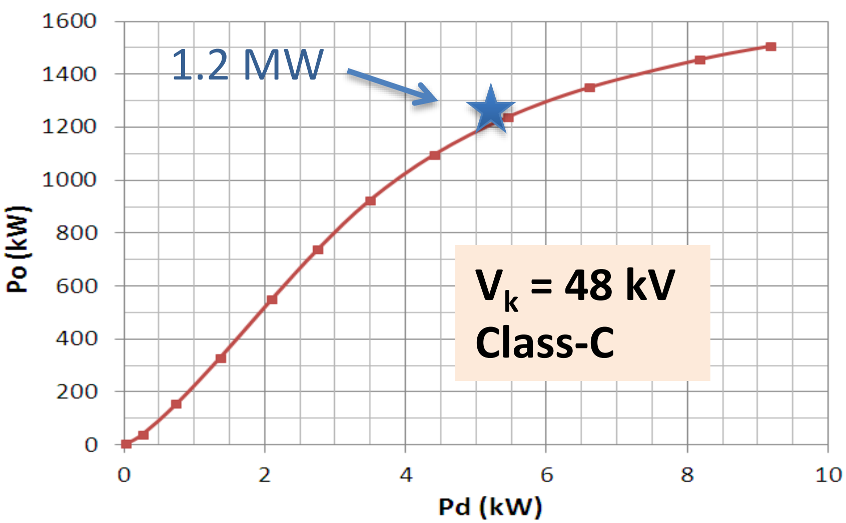




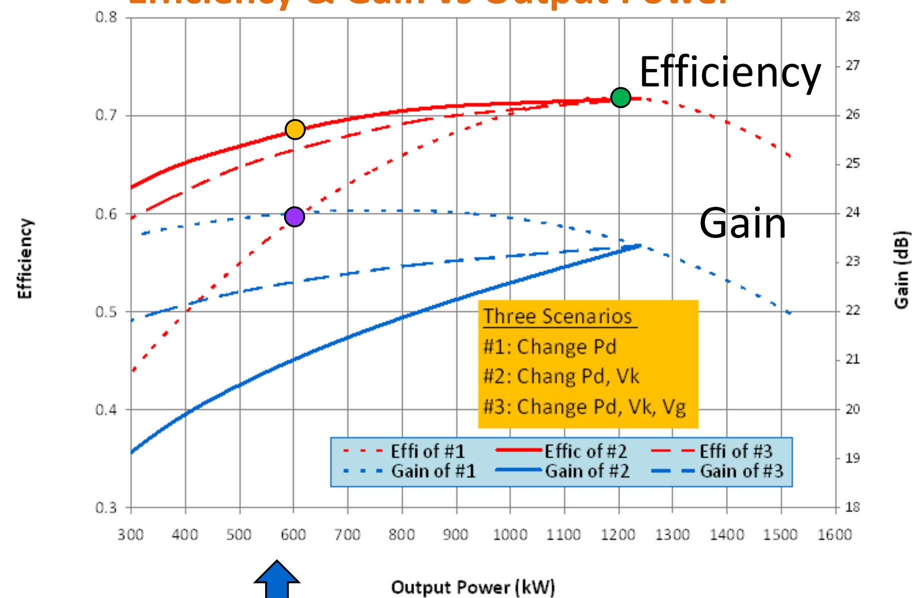
- **Modeling approach is to add phase and current variations between successive bunches in MAGIC-2D**
- **Efficiency is not sensitive to current variation**
- **Efficiency is not sensitive to phase variation up to 30°**

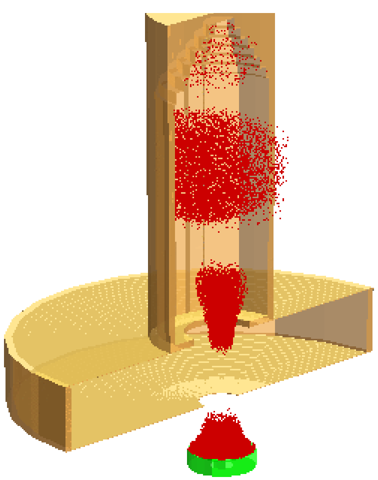
MAGIC Prediction of MB-IOT Performance Courtesy of Thales and CPI

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

Solid State Driver

TOMCO 15 kW driver being used for Factory Testing at L3

Single Rack Configuration

Operating Frequency	**699 – 709 MHz**
Output Power for 5 dBm input	15 kW PEP
Gain linearity	+/- 0.5 dB
Pulse width	Up to 4 ms
Duty	Up to 10%

Factory Test Results for 15 kW TOMCO Driver

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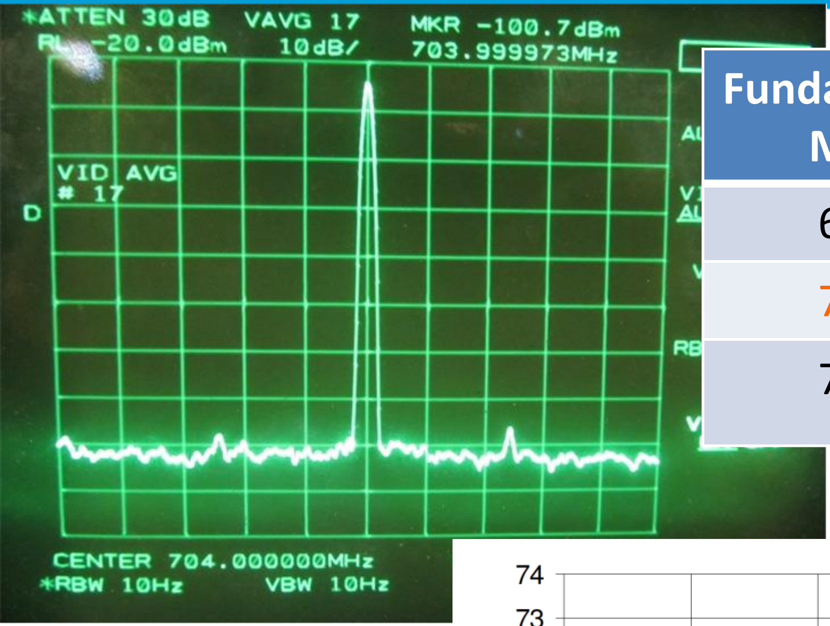
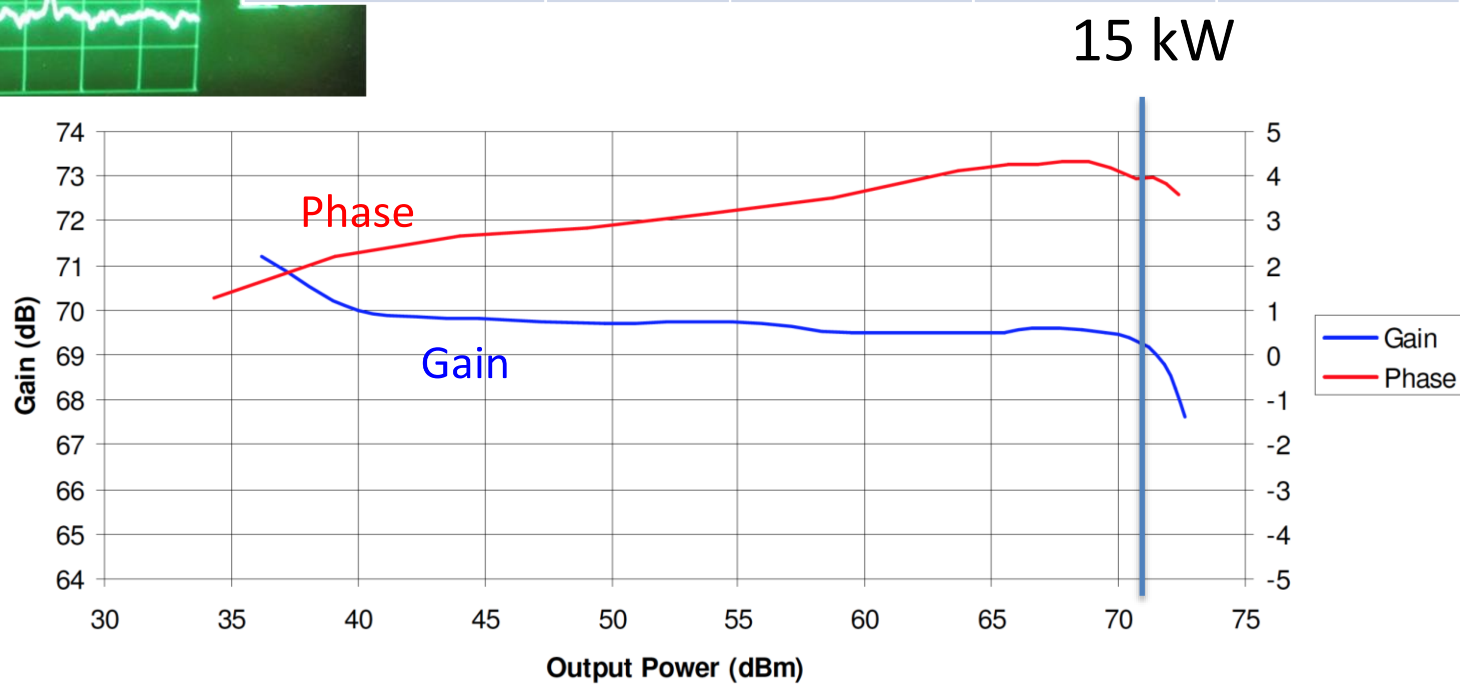


Fundamental MHz	2nd	3rd	4th	5th
699	-41 dBc	<-70 dBc	<-70 dBc	<-70 dBc
704	-40 dBc	<-70 dBc	<-70 dBc	<-70 dBc
709	-45 dBc	<-70 dBc	<-70 dBc	<-70 dBc

No spurious output detected above -70 dBc



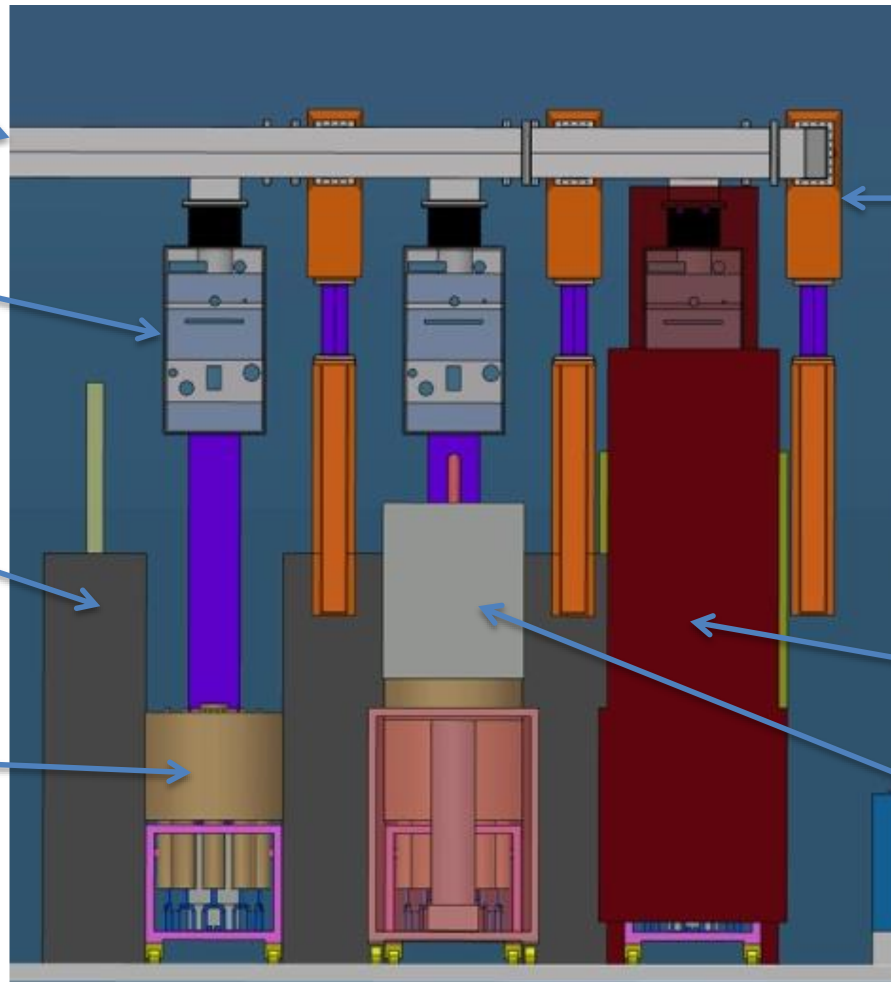
Comparison of Space envelopes

Waveguide

Space allocated for HV Deck for Grid and Filament supplies

IOT Driver Rack

L3 IOT

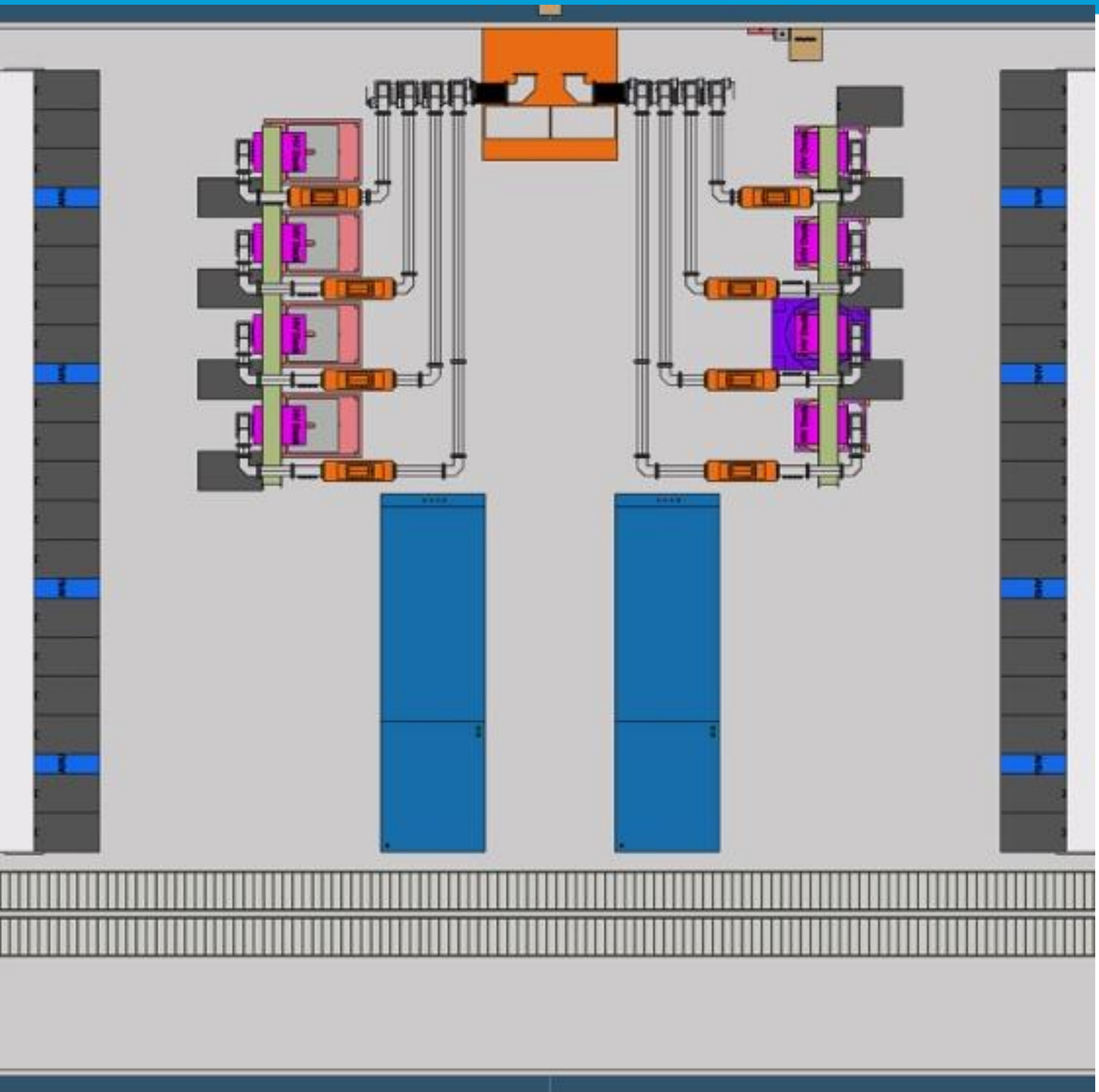


4.5 m from the floor

704 MHz Klystron

Thales/CPI IOT

Possible Gallery Layout



Layout compatible with Klystron layout (Important for utilities and building constraints)

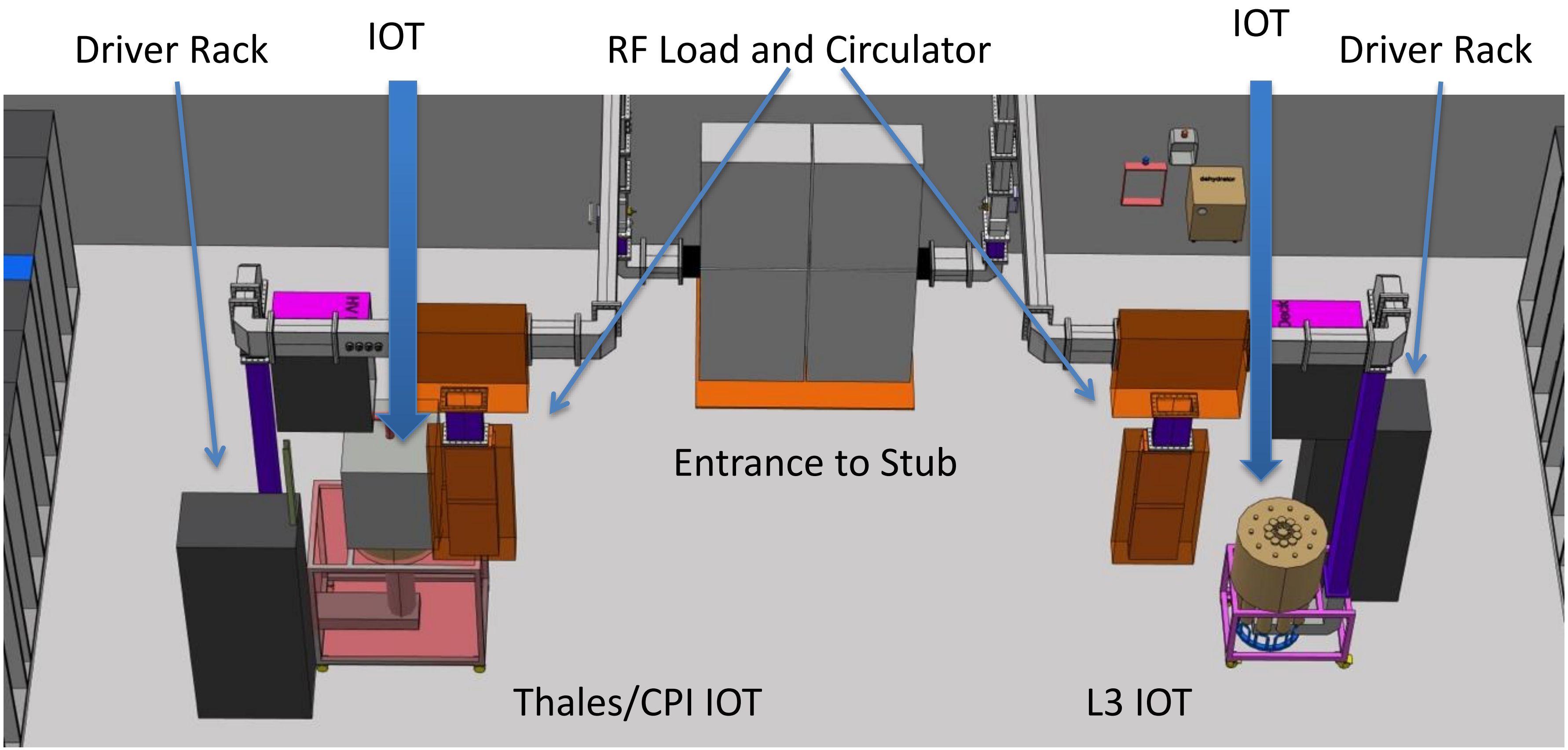
Gallery design compatible with both MB-IOT designs
4 Tubes per HV supply

One driver rack per MB-IOT

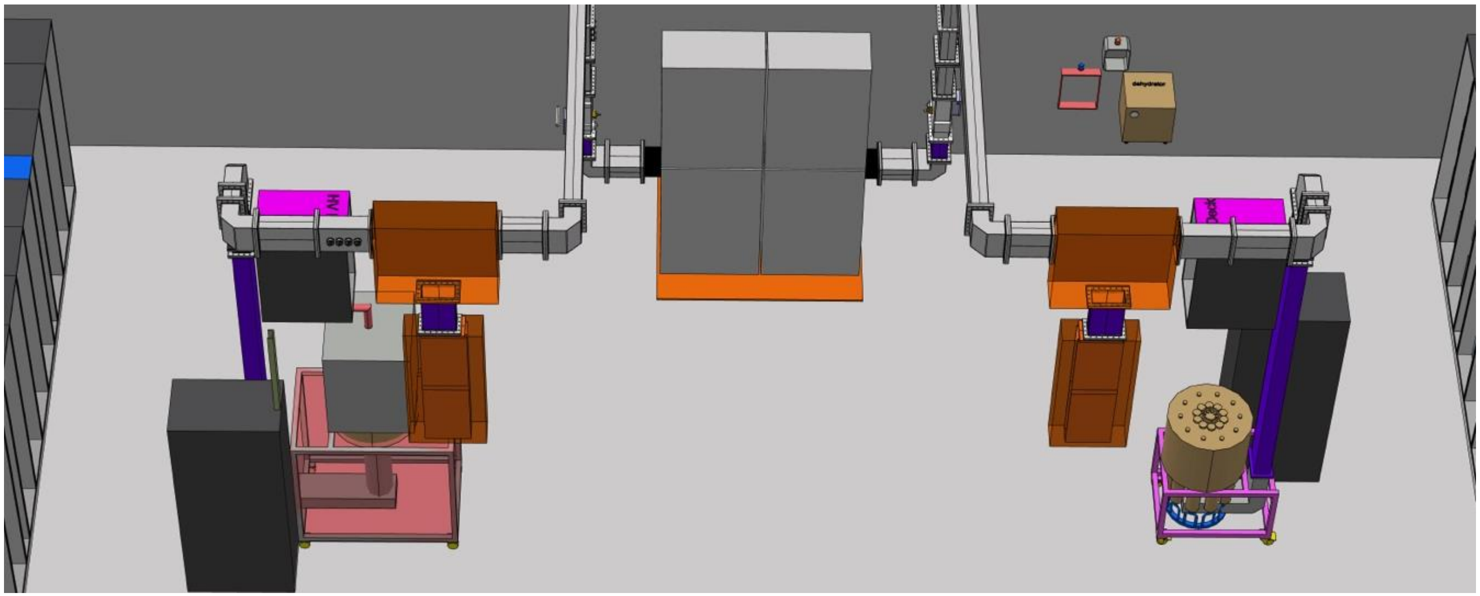
HV-Deck for Filament and Grid supplies placed above the tube (Details will depend on final filament/grid requirements)

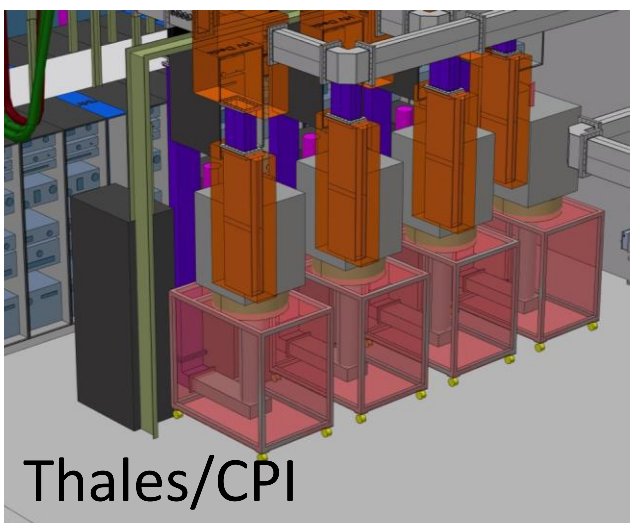
Possible Gallery Layout

IOTs in Isolation showing RF Chain from tube to cavity

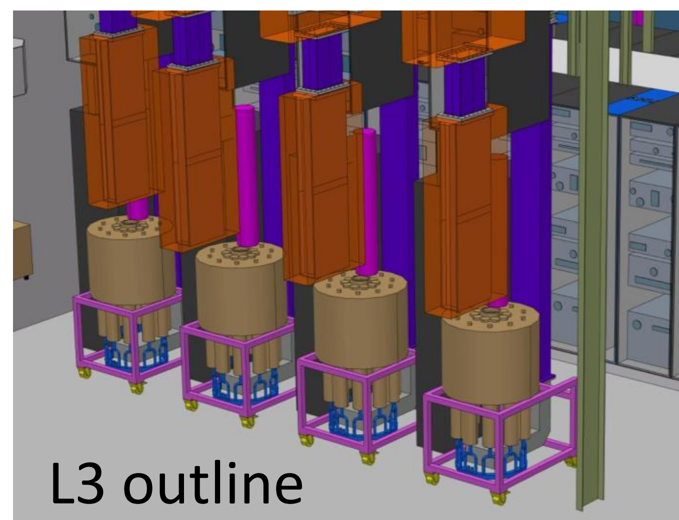


Side view of groups of 4 IOTs



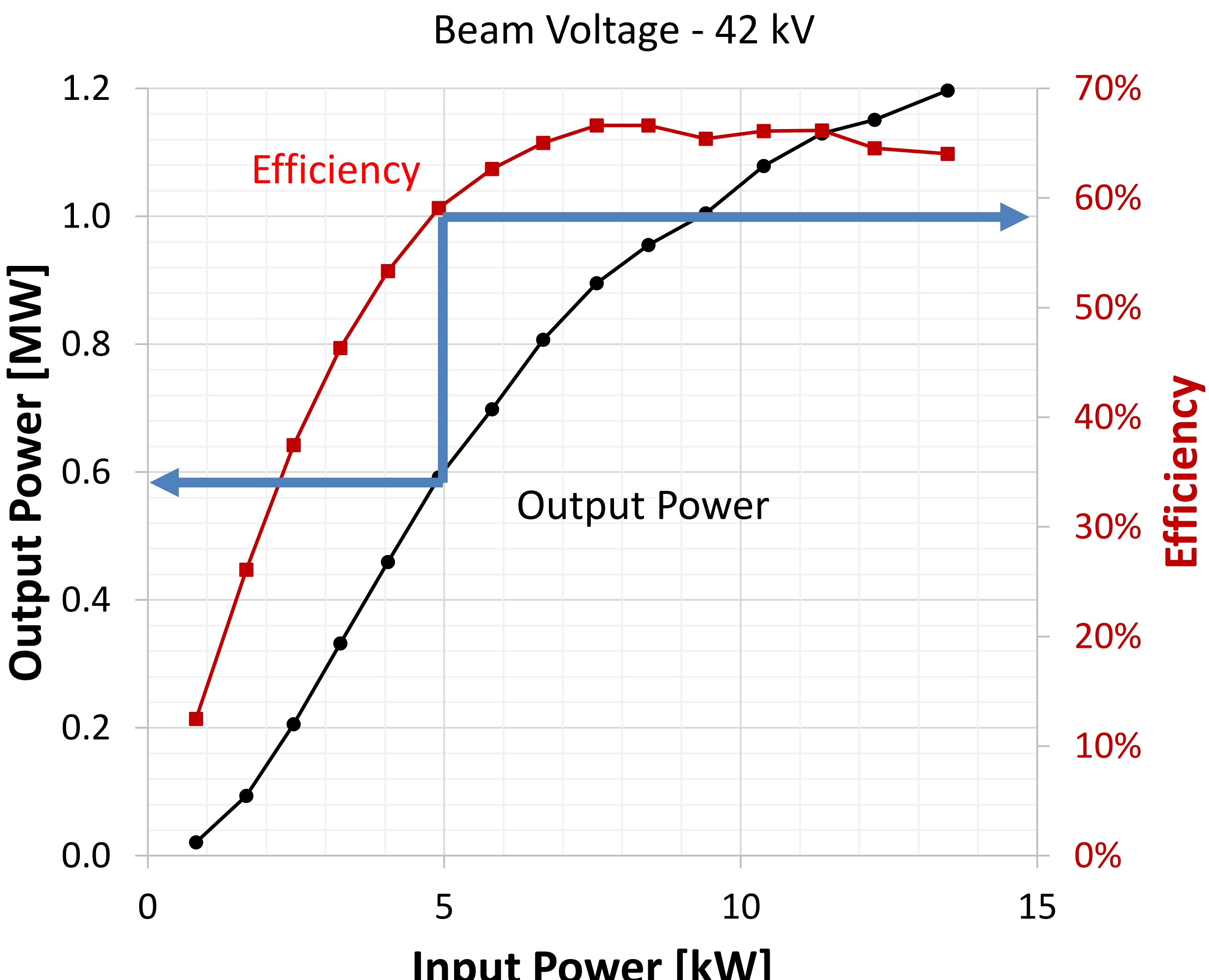


Thales/CPI



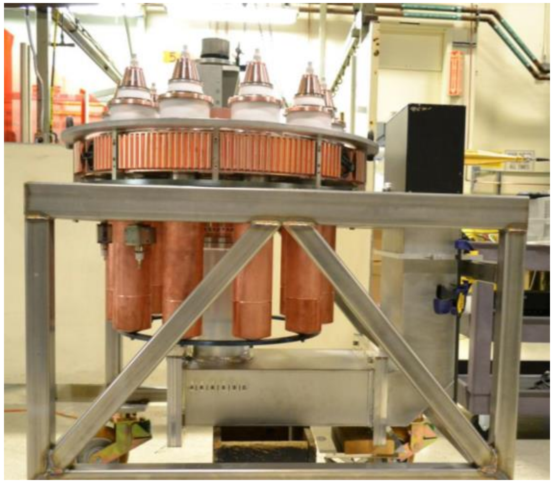
L3 outline

Preliminary Results



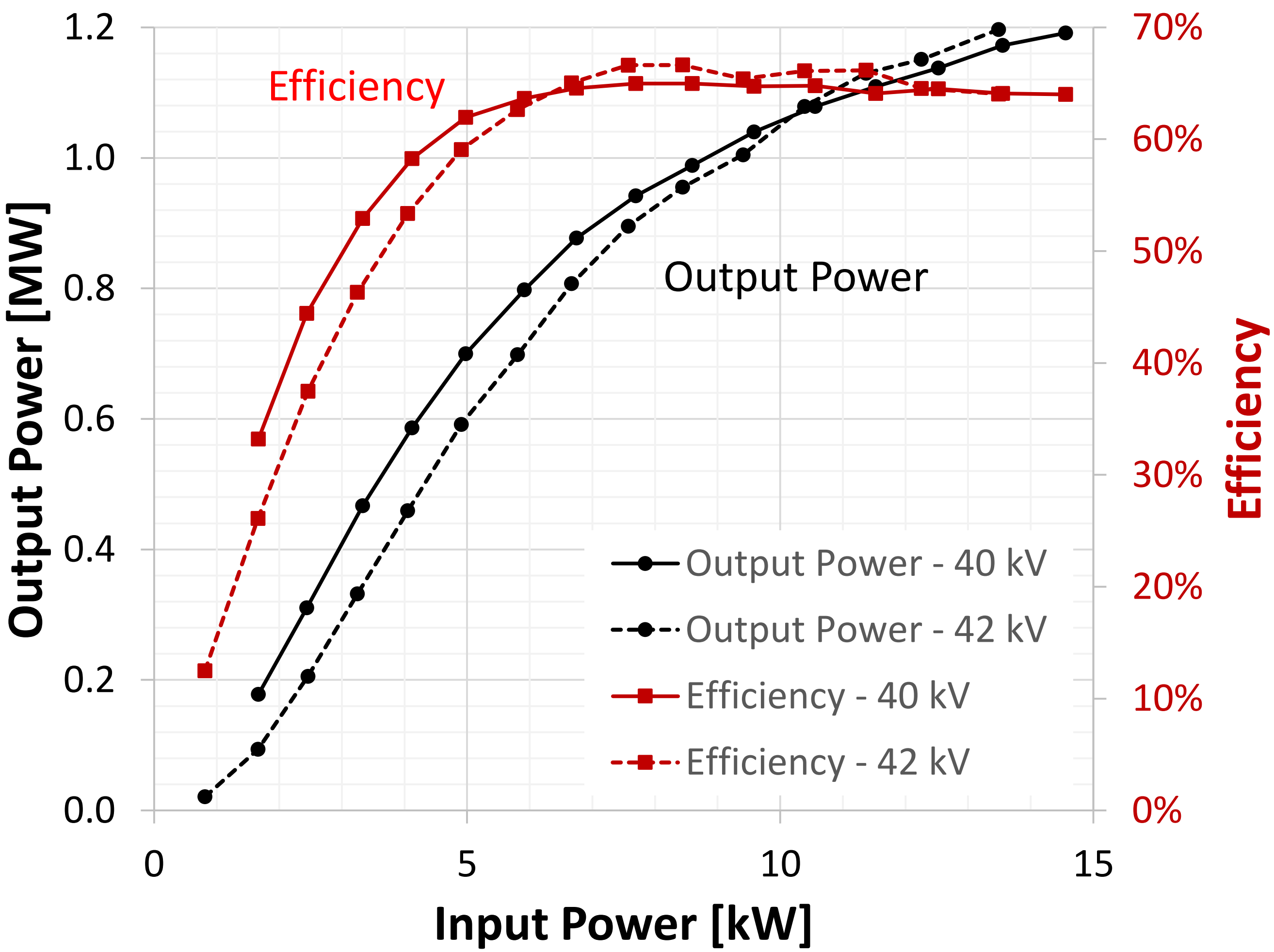
Efficiency > 60% from 600 kW to 1.2 MW

(HV efficiency only)



Courtesy of L3

Preliminary Results



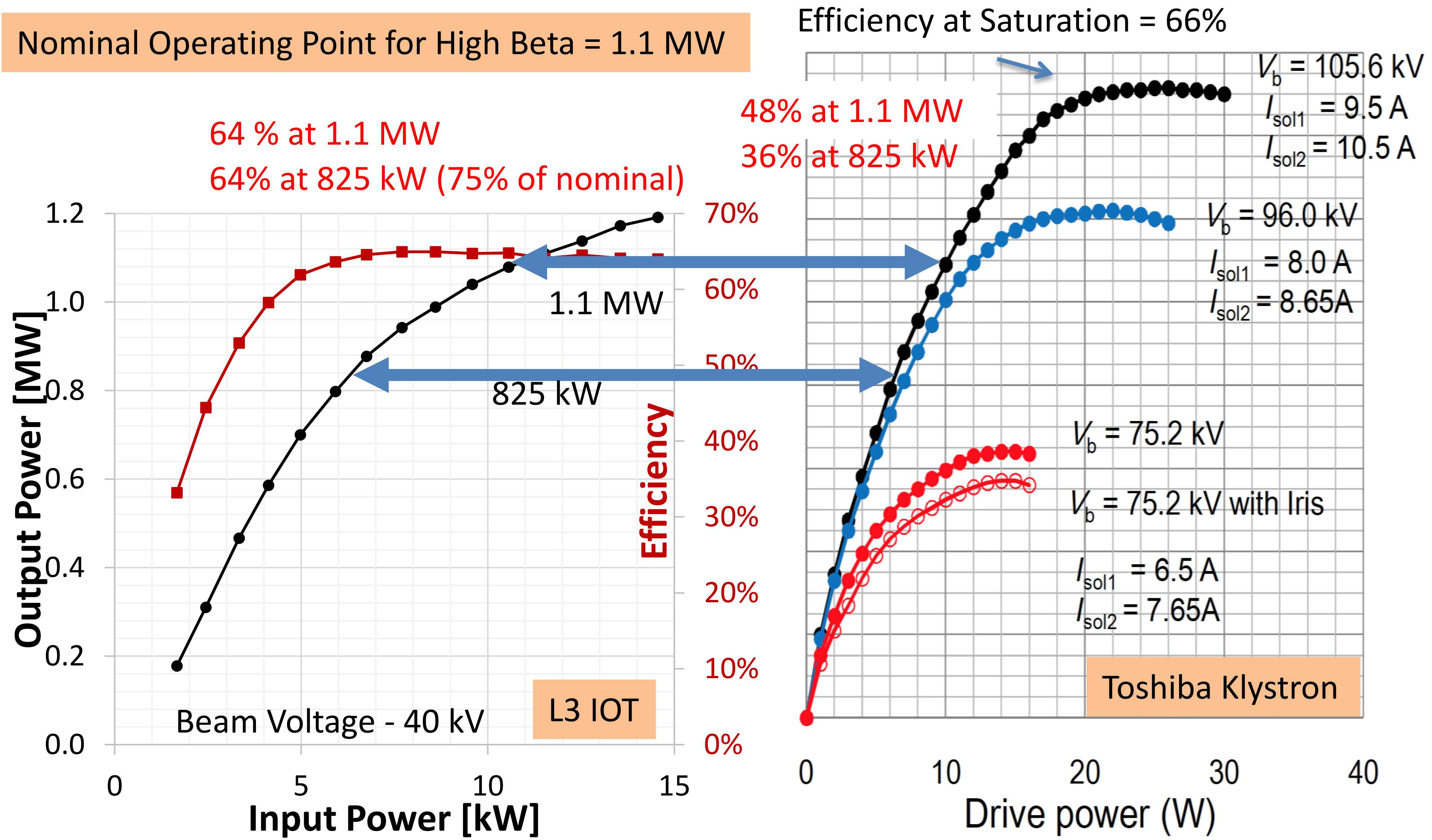
Efficiency and gain improves with higher voltage

Design Voltage 45 kV

- Currently limited by test stand

Courtesy of L3

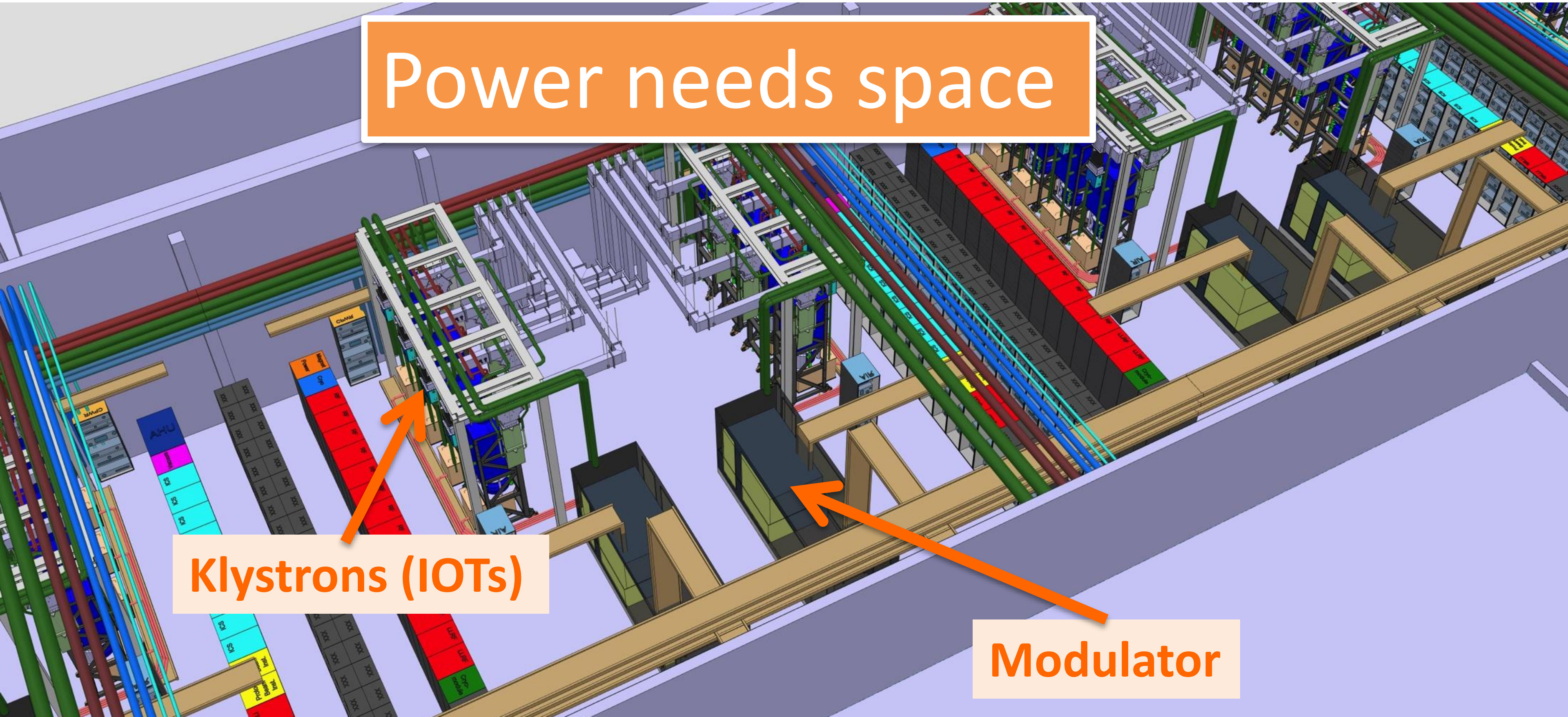
Comparison to Klystron



Elliptical (704 MHz) RF System Layout

Space available = 130 m^2
Installed RF Power 8 x 1.5 MW = 12 MW
---> 90 kW / m^2

Solid State solution:
15 kW/rack = 100 racks excl. combiners etc.



Conclusions and Status 1/2

- Staged installation pre/post 2019 allows time for new development for HB Linac

- In kind contributions for HB (84 systems) already committed including:
  - Cryomodules
  - Waveguide, circulators and RF Loads
  - Interlock and control systems
  - Racks, utilities and cooling

  Modulators and Klystrons are included in scope contingency (could delay procurement)

- Site construction well under way
  - Tunnel structure complete
  - RF Gallery progressing well
  - First handover including utilities in February 2017

- 80% beam power comes from the High Beta Linac
- Demanding energy targets demand new development including taking on some risk

Conclusions and Status 2/2

- Contracts placed for two IOT technology demonstrators (Thales/CPI and L3)
- Both designs complete
- Thales/CPI construction started
  - Tube delivery expected November 2016
  - FAT/SAT expected End of January 2017
- L3 IOT already under test in the factory
  - 1.2 MW achieved
  - Efficiency > 60% from 600 kW to 1.2 MW
- 15 kW solid state driver delivered by Tomco
- Test stand for extended testing and soak testing progressing at CERN
- Discussions of further testing in Lund started
- Pre-series for industrialisation under consideration

We thank

The teams at Thales and CPI for material

Mark Kirshner and his team for material and for allowing me to take part in the early testing

Eric Montesinos and his team for his preparations for testing at CERN

Yesterdays Webcam of Part of the ESS Site