IOTs for ESS

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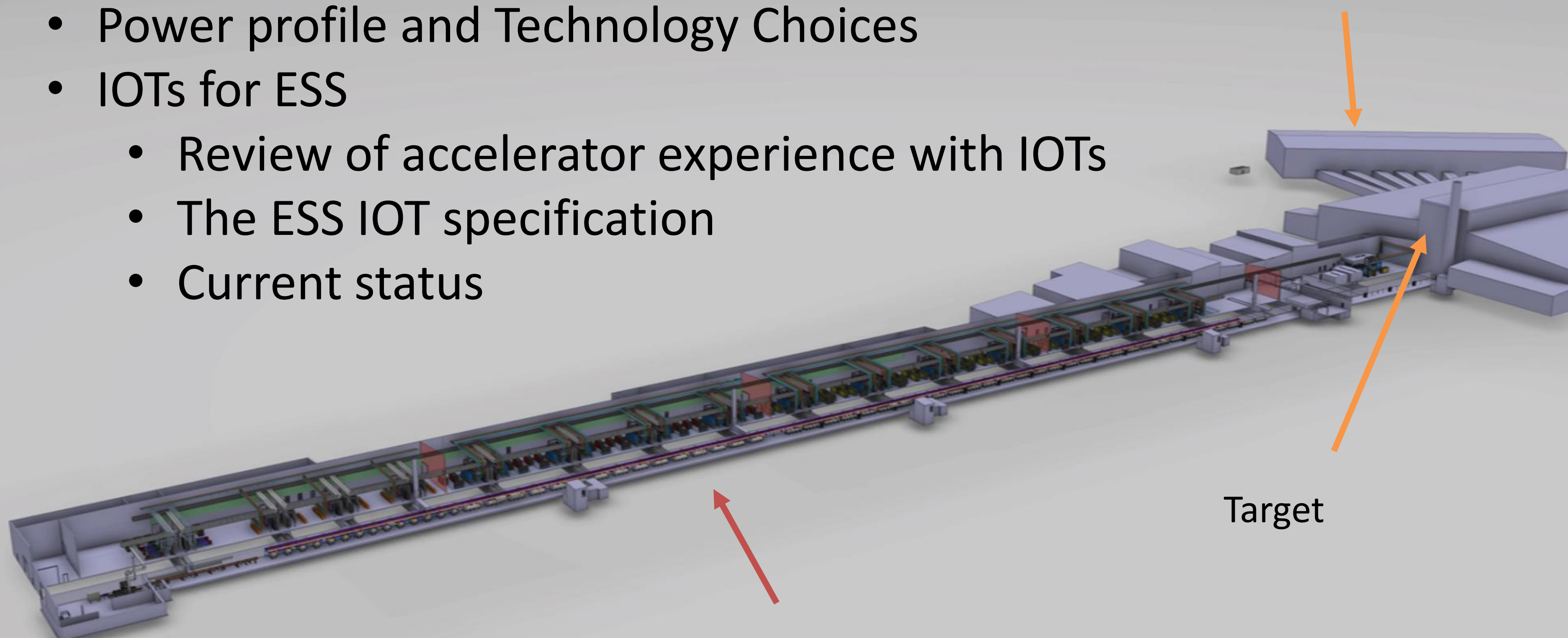
Agenda

- Introduction to ESS
- Power profile and Technology Choices
- IOTs for ESS
    - Review of accelerator experience with IOTs
    - The ESS IOT specification
    - Current status



Overview

- The European Spallation Source (ESS) will house the most powerful proton linac ever built.
  - The average beam power is five times greater than SNS.
  - The peak beam power will be over seven times greater than SNS
- The linac will require over 150 individual high power RF sources
- **We expect to spend over 200 M€ on the RF system alone**

Neutron Spallation Sources

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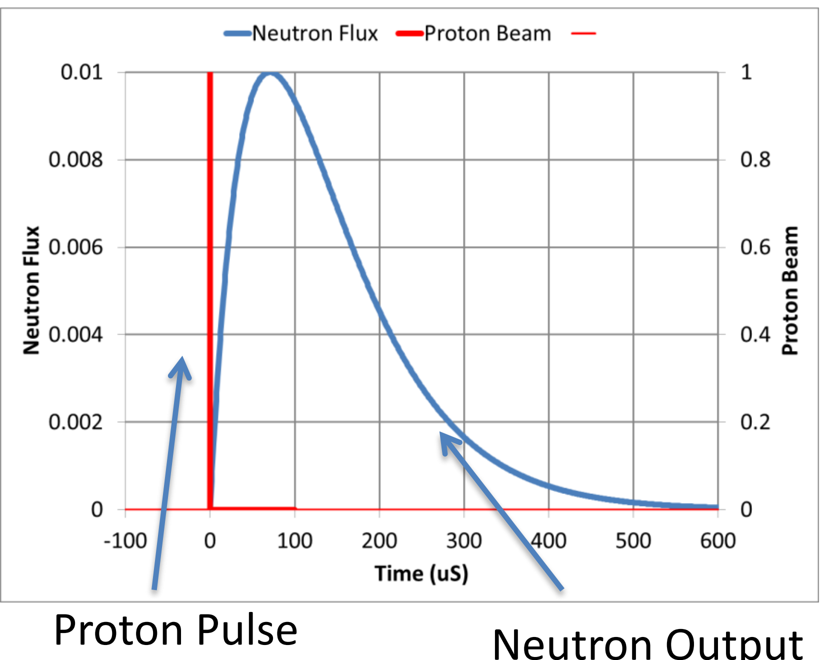
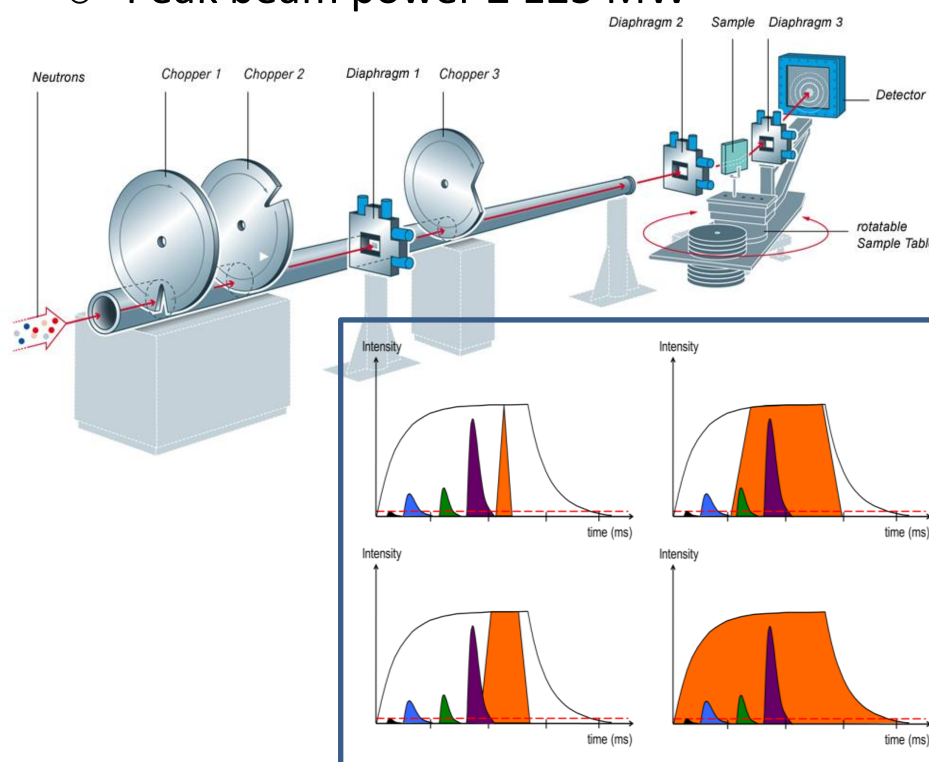
Short Pulse Concept

- Protons stored in circular accumulator
- Accumulator ring of 300 m = 1 µs
- Neutrons cooled in moderator following impact on target
- Neutron time constant = few 100 µs
- Short pulse at ESS power would destroy target or a 100 µs ring would be around 30 km



Long Pulse Concept

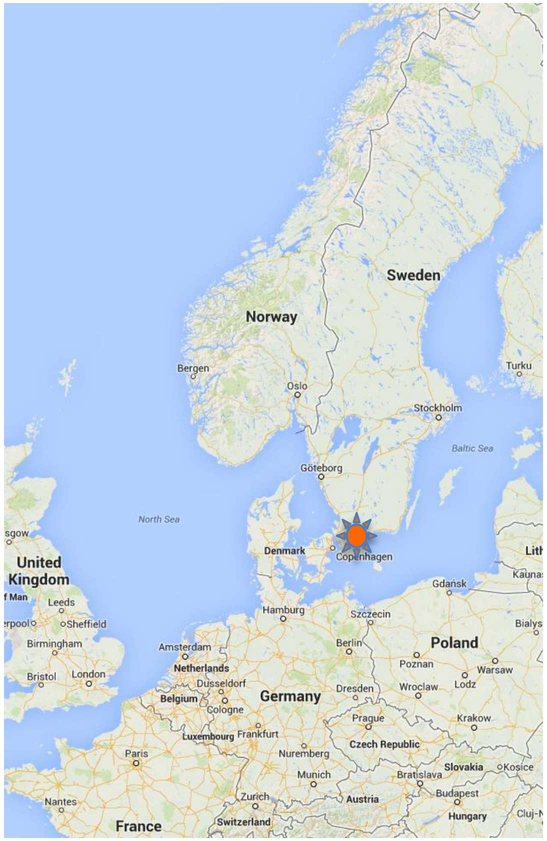
- No accumulator
- Neutrons still cooled in moderator following impact on target
- Choppers and long beam lines provide energy measurement
- Peak beam power ≤ 125 MW



The European Spallation Source

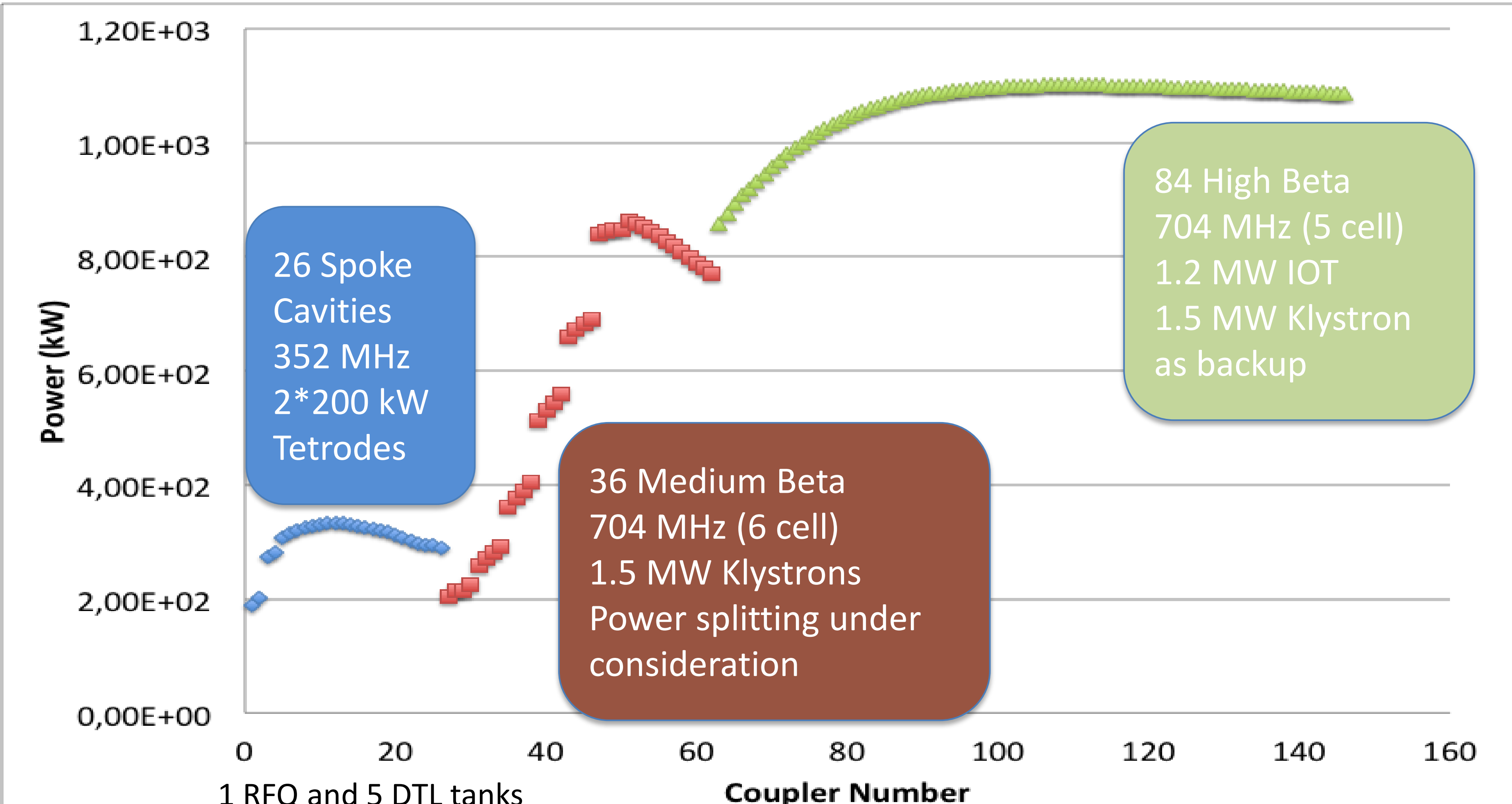
ESS is a

- long-pulse neutron spallation source based on a large linac
- Proton linac designed for 5 MW average power
- European project located in the southern part of Sweden



The ESS Superconducting Power Profile

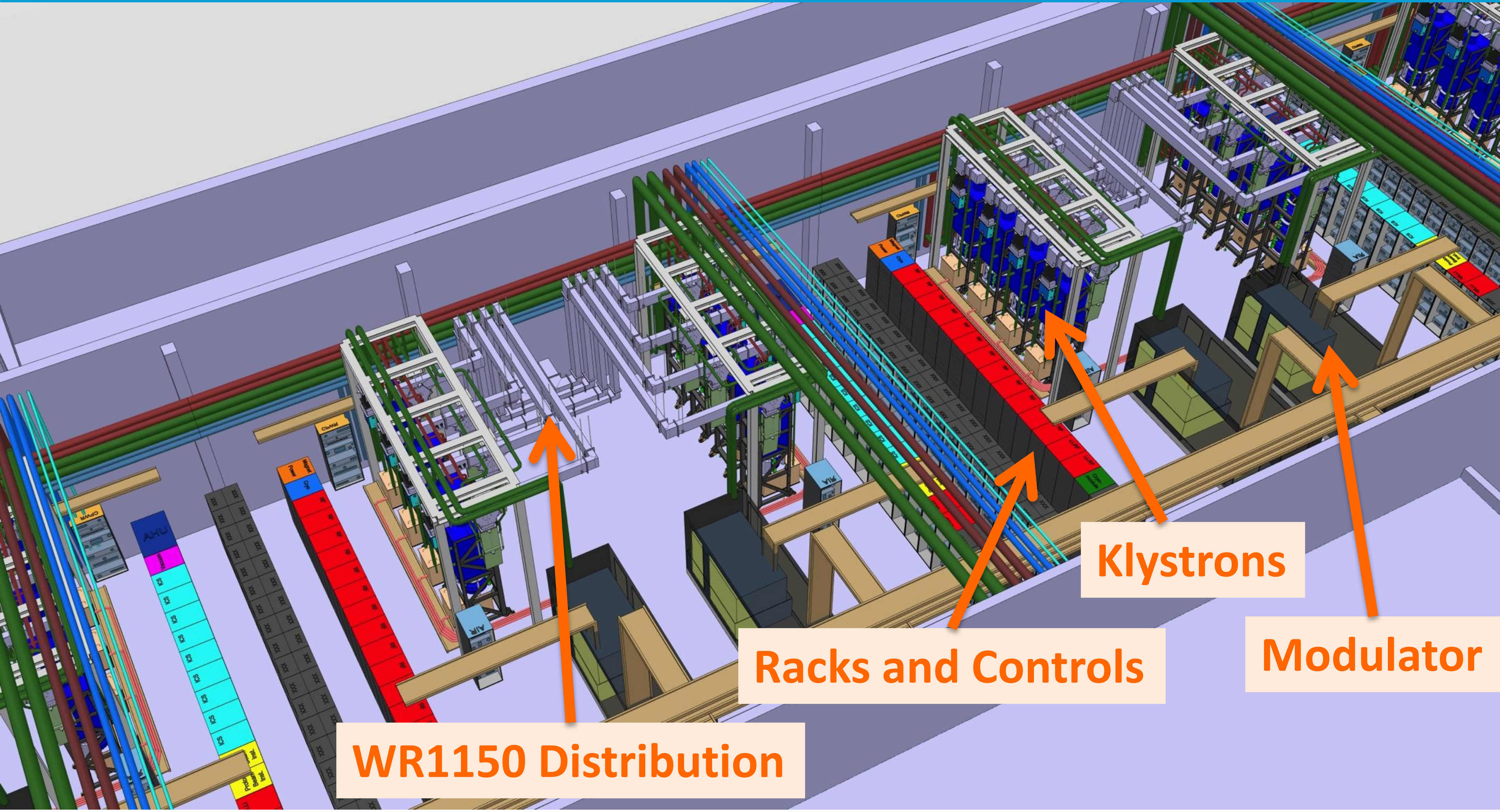
> 150 cavities/couplers



1 RFQ and 5 DTL tanks
352 MHz
2.8 MW Klystrons

125 MW peak (4% duty)
5 MW average

Elliptical (704 MHz) RF System Layout



4.5 Cells of 8 klystrons for Medium Beta

10,5 Cells of 8 klystrons (IOTs) for High Beta

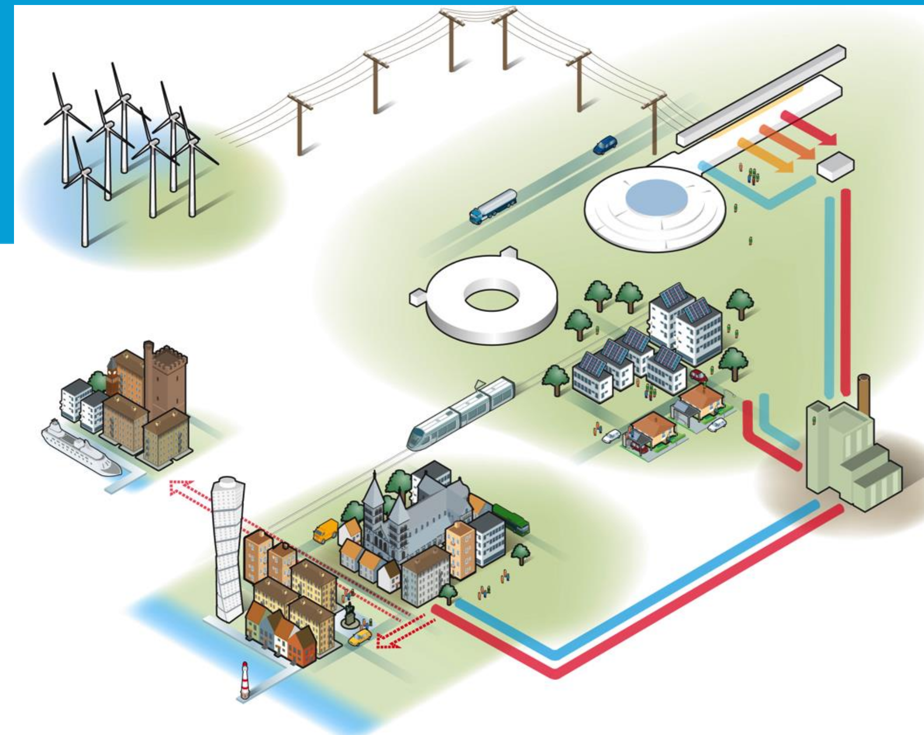
Where next?

The ESS Requirement

Carbon Neutral

Innovative

Green



Time to develop Super Power IOT

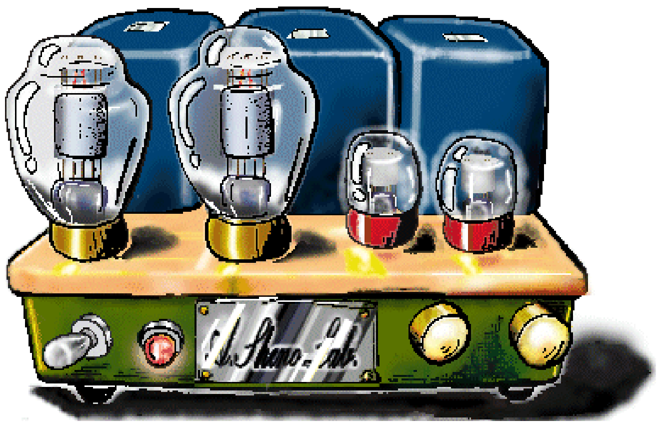
Accelerating Structure	Freq. (MHz)	Quantity	Max Power (kW)
RFQ, DTL	352	5	2200**
Spoke	352	30	330**
Elliptical Medium Beta	704	34	860**
Elliptical High Beta	704	86	1100**

** Plus overhead for control

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'

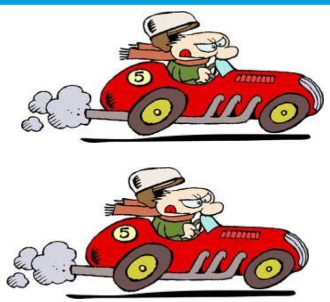
How does the IOT work?

Source

Beam

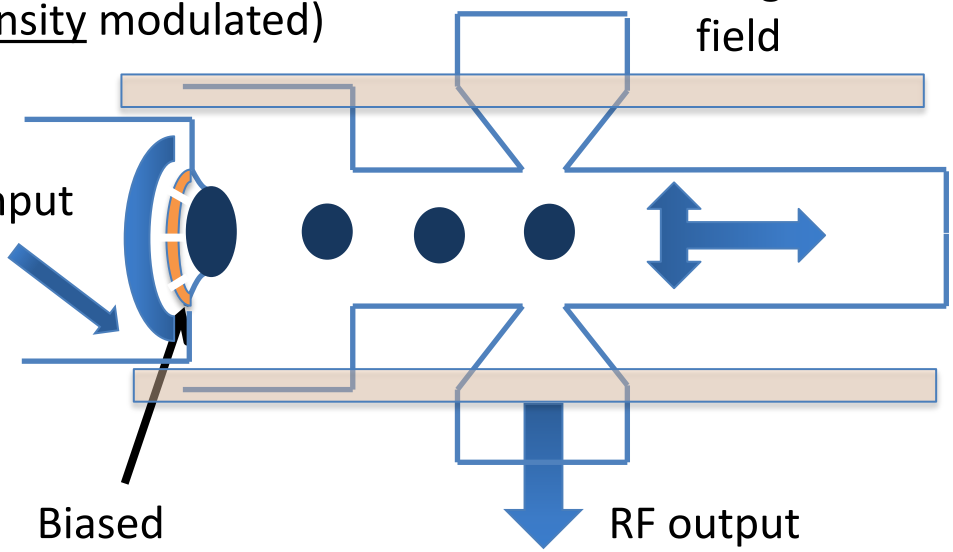
Control

Acceleration



Deceleration = RF Output

IOT
(Density modulated)



Reduced velocity spread compared to klystrons

Higher efficiency

No pulsed high voltage

A Questionnaire

(This will take one minute of your time and will help us to improve our service to you!)

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Who here believes that high efficiency is a good thing?

Do we really need overhead for LLRF?

Do we <u>like</u> to operate below absolute maximum output power to improve reliability?

Is the efficiency at <u>saturation</u> really the most important measure?

Need to consider the whole system and the actual point of operation

The Performance Comparison

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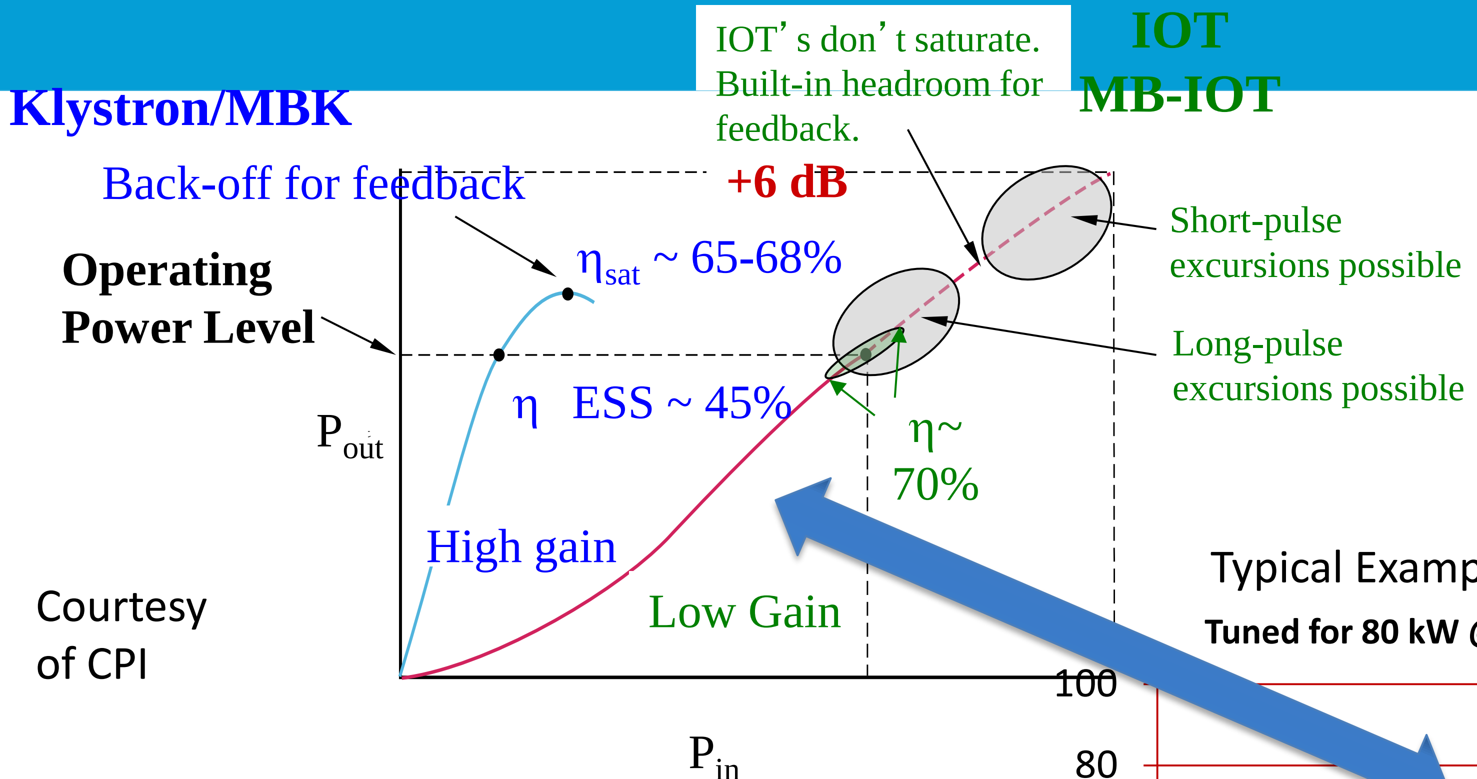
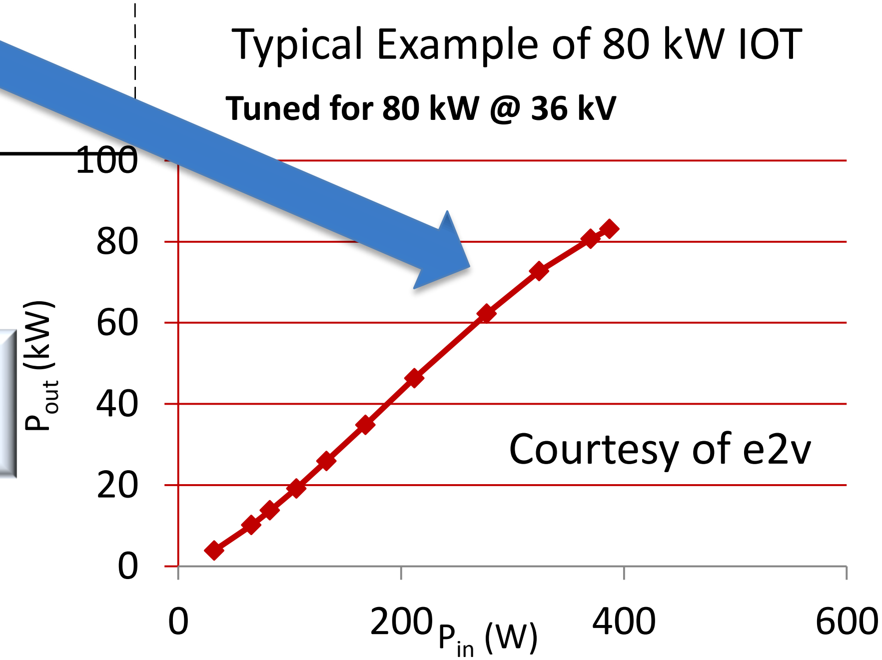


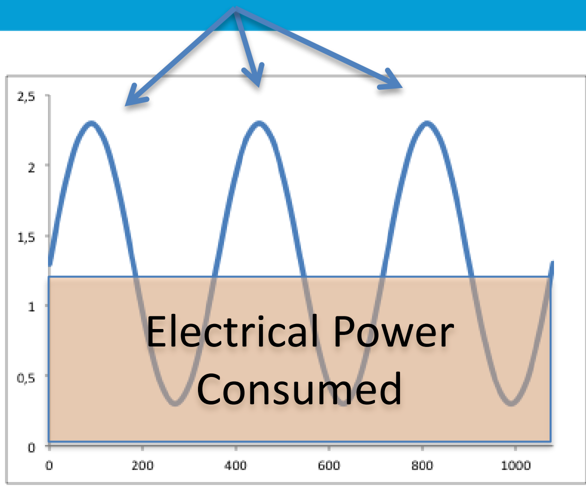


Klystrons: Back-off for feedback cost 30%
IOTs: Operate close to max efficiency

Another Cartoon!

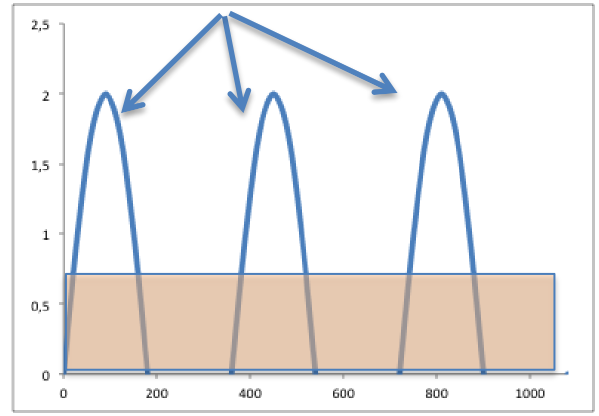
Klystrons

Power delivered to beam



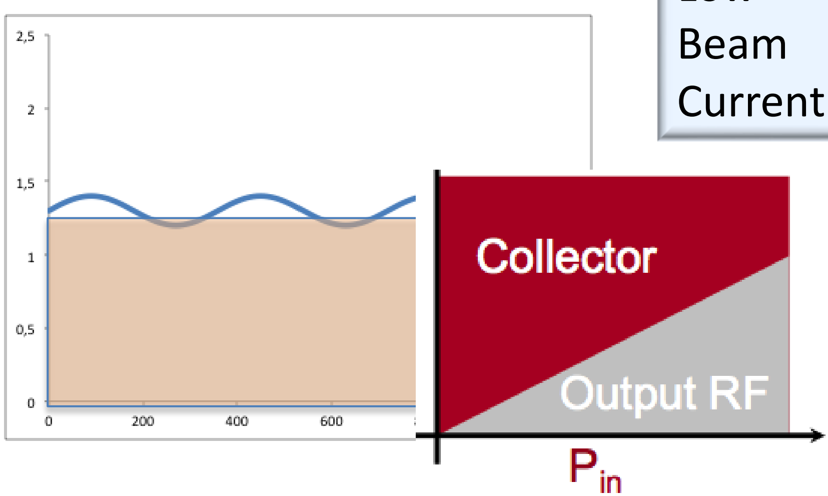
IOTs

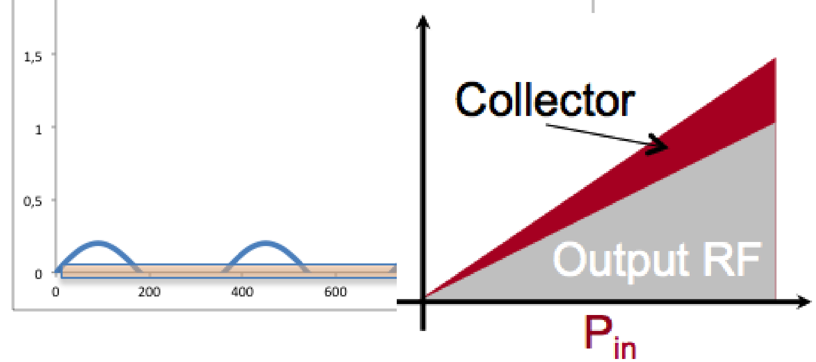
Power delivered to beam



High Beam Current

Low Beam Current





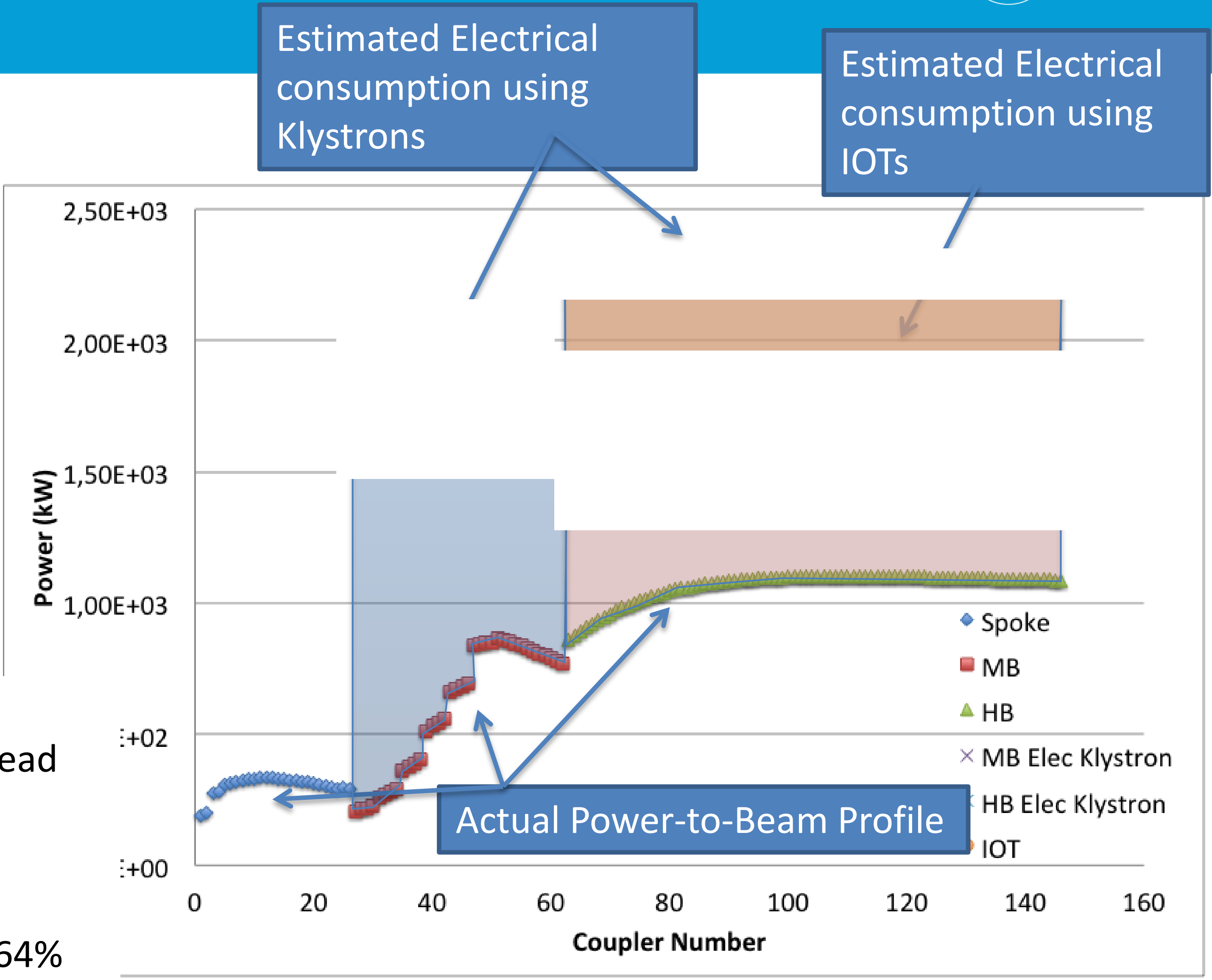
An RF Source for a Proton Linac

Operation point below saturation for regulation reduce actual efficiency

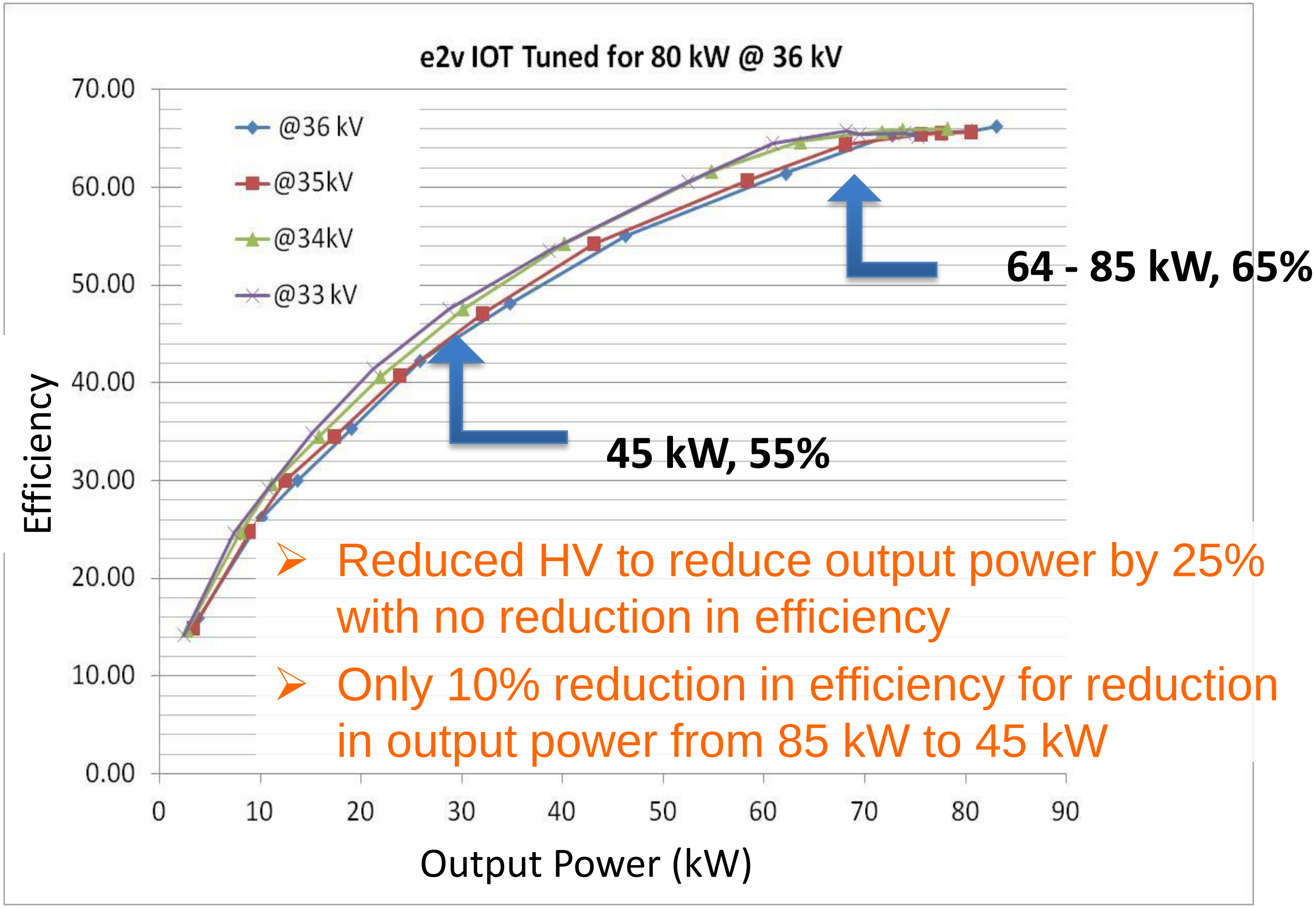
Each marker is an RF Source

Assume:
20%+5% klystron overhead
5% IOT overhead

Modulator η= 93%
Klystron saturation η = 64%
IOT η = 65%

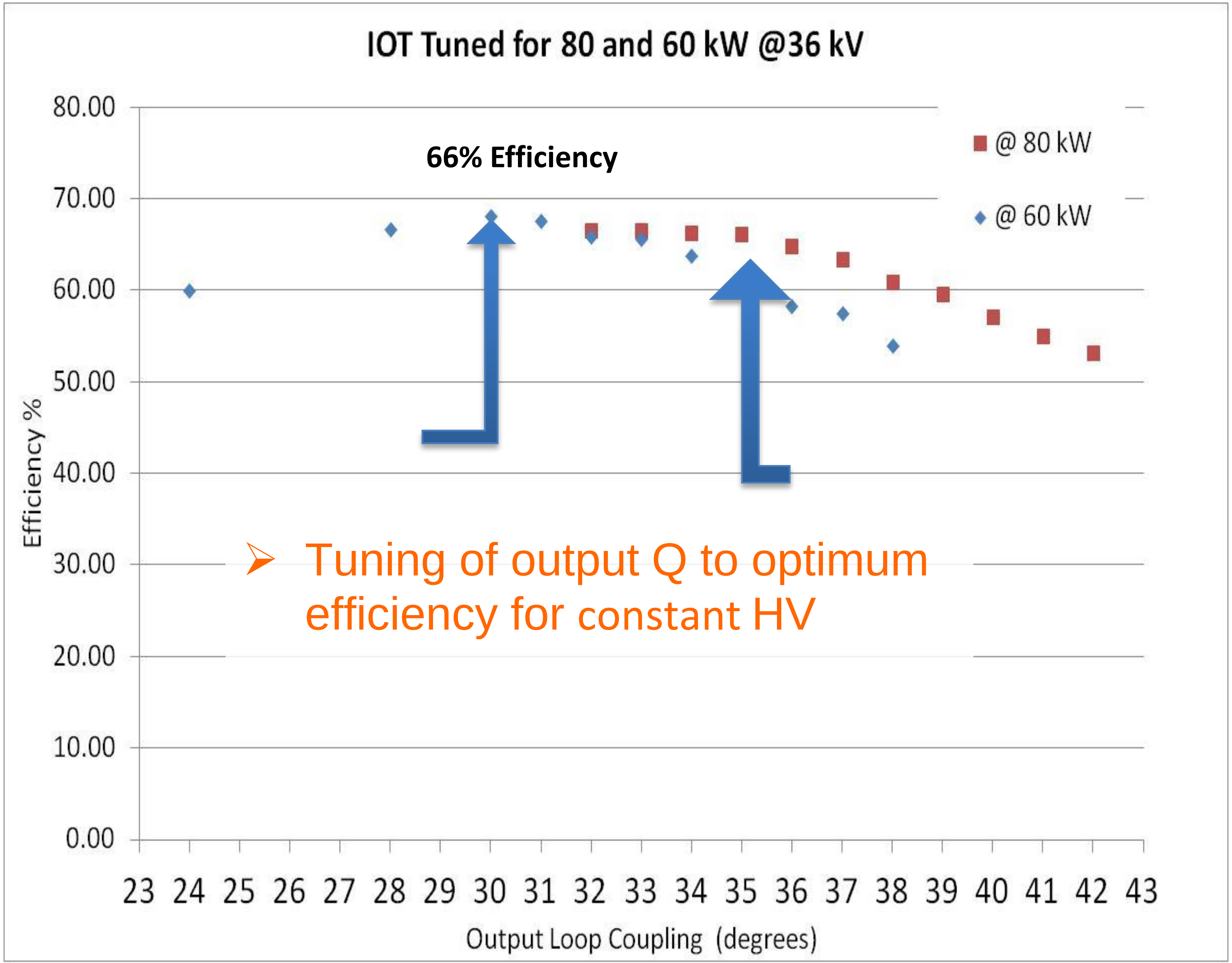


Typical Results (Broadband Broadcast IOT)



- Reduced HV to reduce output power by 25% with no reduction in efficiency
- Only 10% reduction in efficiency for reduction in output power from 85 kW to 45 kW

Typical Results (Broadband Broadcast IOT)



- Tuning of output Q to optimum efficiency for constant HV

Selection of Laboratories currently using IOTs

Accelerator	Type	Number of IOTs in use	IOTs in use	Typical operation
Diamond Light Source	Synchrotron Light Source	8 in use 4 on test stand 1 on booster	TED e2v L3	CW operation (500 MHz) Typically 50-60 kW each Combined in groups of 4
ALBA	Synchrotron Light Source	12 in use 1 on test stand	TED	CW operation (500 MHz) Typically 20-40 kW each Combined in pairs
Elettra	Synchrotron Light Source	2 in use	TED e2v	CW operation (500 MHz) Initially ~ 65 kW with one tube, now ~ 35 kW
CERN	Injector for LHC	8 (planned) Currently on test	TED	CW operation (801 MHz) 60 kW each
BESSY	Synchrotron Light Source	1	CPI	CW operation Up to 80 kW
NSLS II	Synchrotron Light Source	1 on booster	L3	CW tested Up to 90 kW Normal 1 Hz cycle 1 - 60 kW
ALICE and EMMA (Daresbury Laboratory)	Technology Demonstrator	3 on test	TED CPI e2v	Pulsed (18 ms) 1.3 GHz 16-30 kW

and more …

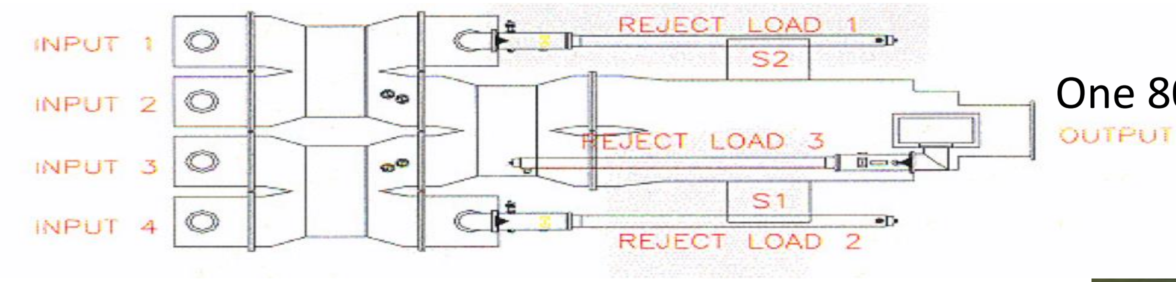
Examples

3rd Generation Light Source Storage Ring

Three 500 MHz 300 kW amplifier for SR

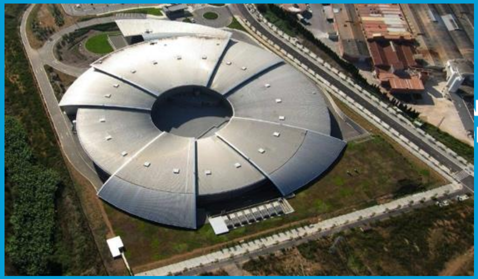
- 4 x 80 kW IOT combined

One 80 kW for the Booster



Examples

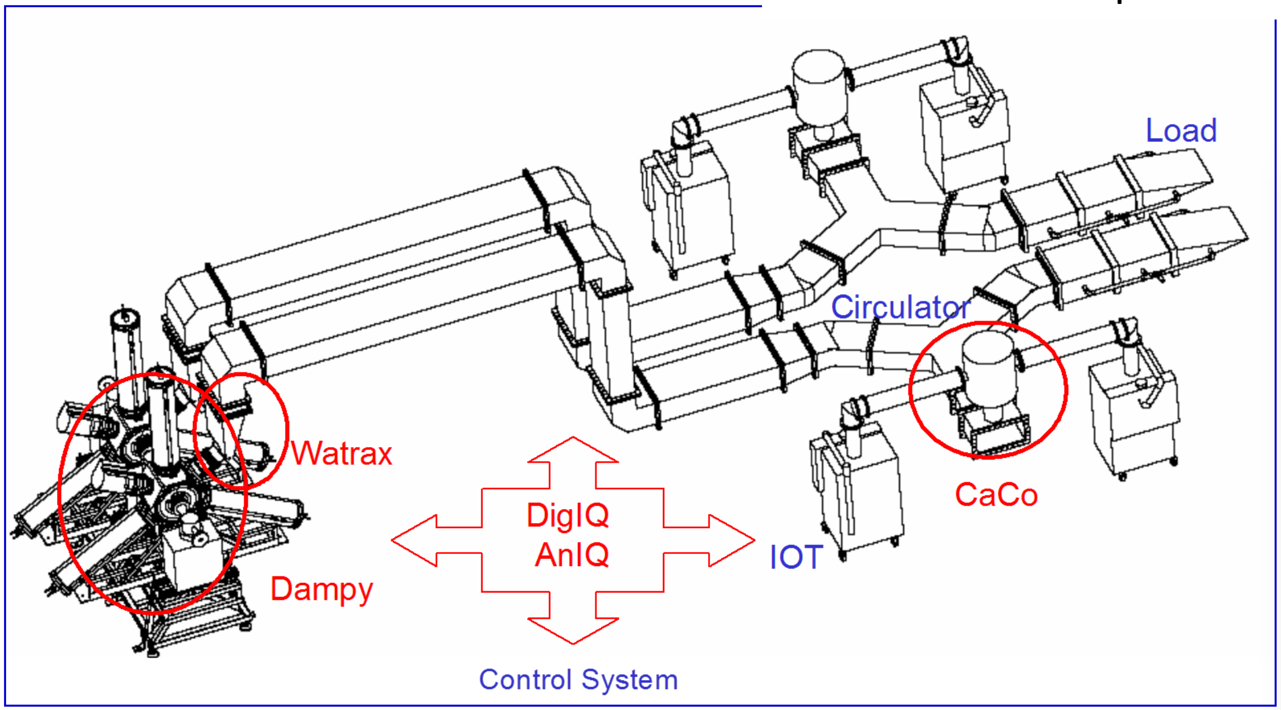
3rd Generation Light Source Storage Ring



Normal conducting cavities
IOTs combined in pairs
(cavity combiner)

6 RF plants of 160 kW
500 MHz
2 IOTs combined per cavity

ALBA
Synchrotron Light Facility



Currently 13 IOT in operation (12 on SR, one on test stand)

Examples

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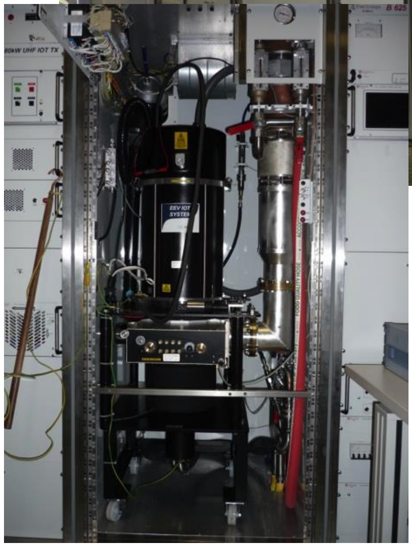
SOURCE

CERN
800 MHz
60 kW

Metrology Light Source
(Willy Wien Laboratory)

CPI 90 kW IOT (K5H90W1)
> 33 000 operating hours



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

ESS IOT Options

- Combine ‘low power’ single beam IOTs by combining output
  - (for example Diamond and ALBA)
  - High number of IOTs for high power
  - More auxiliary supplies, cavities, magnets etc
- Single beam high power IOT
  - High voltage gun (> 90 kV)
  - Large cathode for low charge density
  - High voltage modulator design
- **Multi-Beam IOT**
  - **Reduced high voltage (< 50 kV)**
  - **Low space charge per beam**
  - **Very compact**
  - **High efficiency**

The Super Power IOT Challenge

Multi-beam considerations - The need for more Current

Gun arrangement:

- Individual spherical cathodes
- Distribution of cathodes
- All need consideration on how to get RF into the cathode/grid space
- Phase and amplitude matching of each cathode
- Management of variation in individual cathodes (common HV)
- Mechanical Integrity

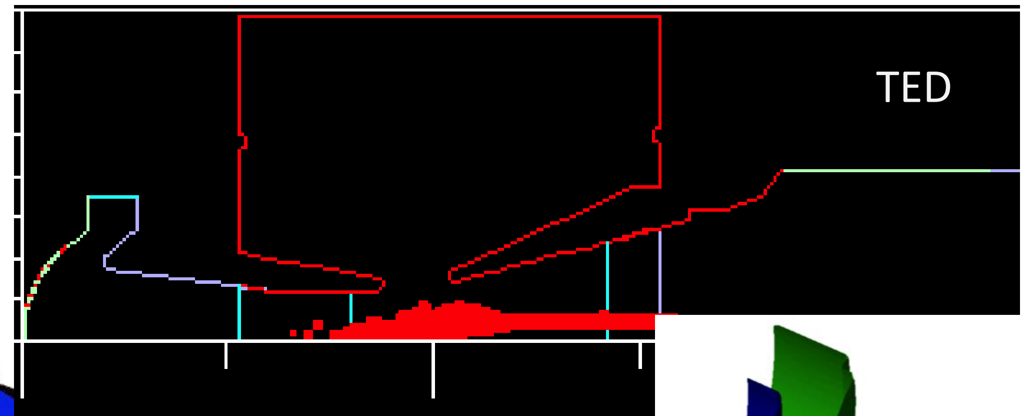
Output cavity:

- Cavity design to interact with multiple beams
- Efficiency combination
- Minimization of sidebands and spurious lines
- Impact on output in case of varying cathode perveance

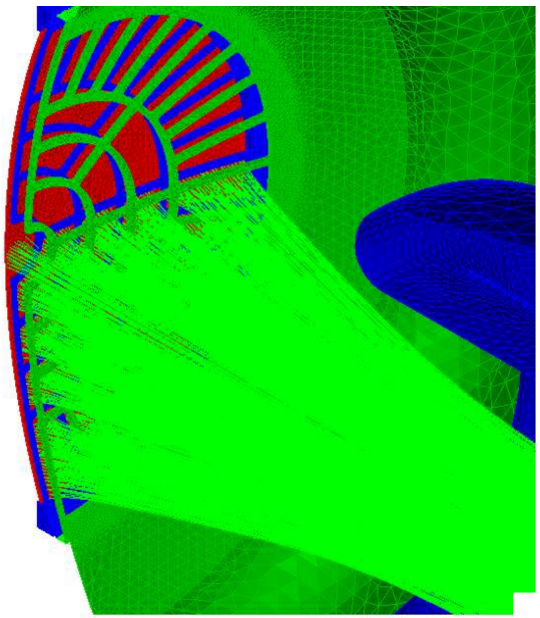
Potentially suitable from 200 MHz to 1.5 GHz or higher

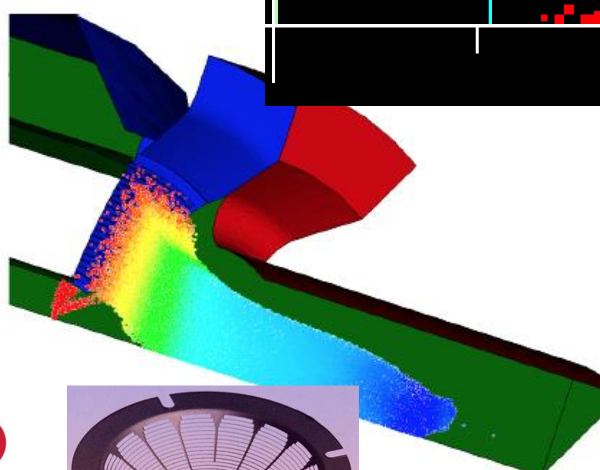
Design and Simulation

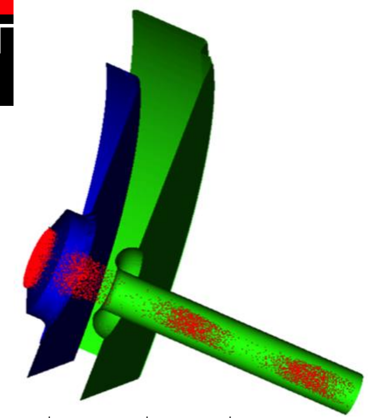
- Analytical and Numerical codes available
- Commercial codes well developed in addition to manufacturers own

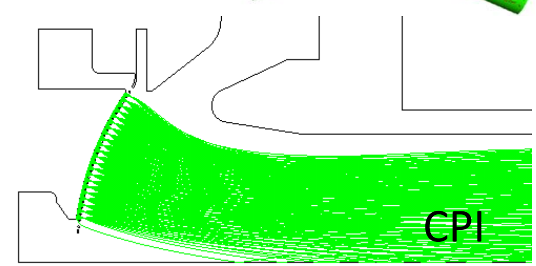


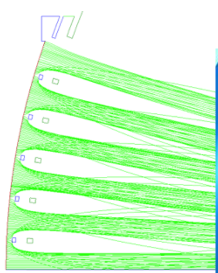
Gun simulation

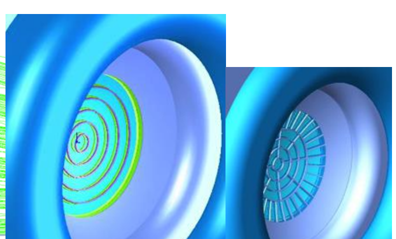


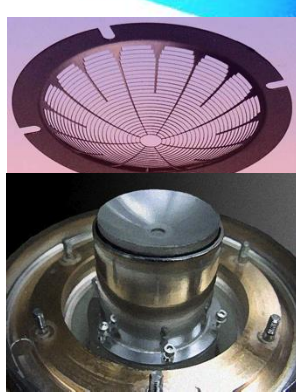




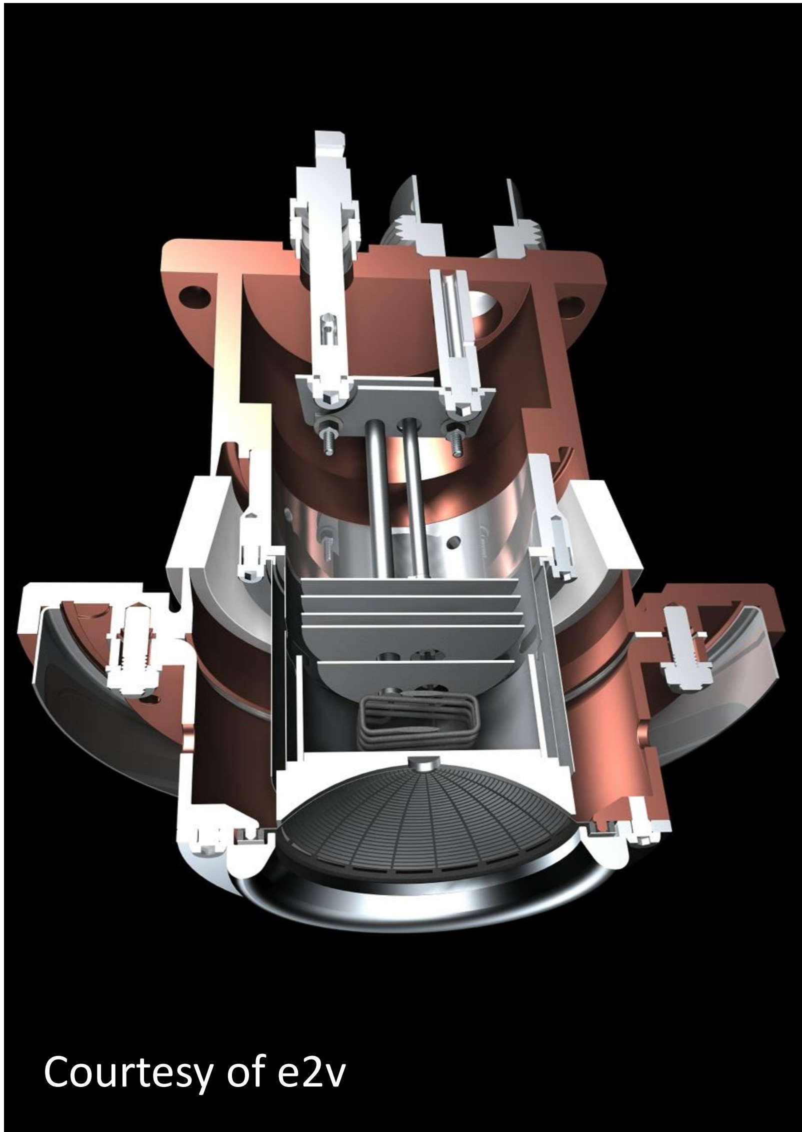








Typical Broadcast IOT



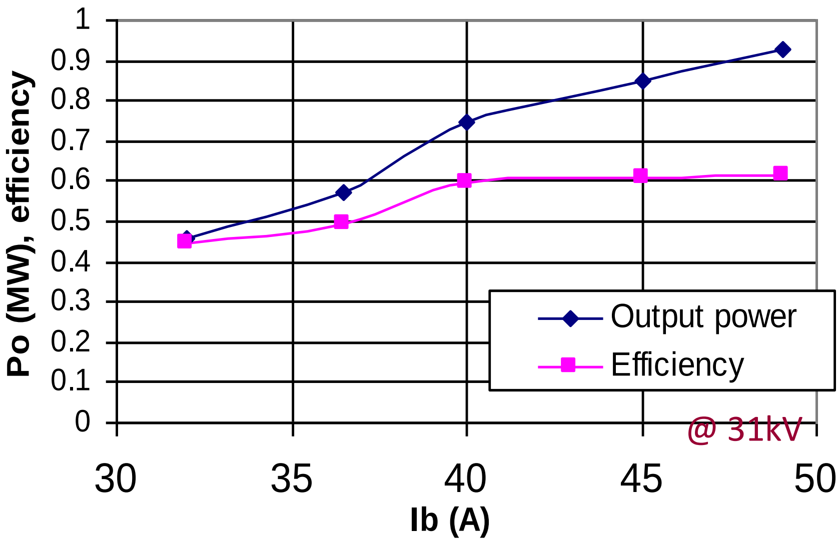
Courtesy of e2v

700 MHz HOM IOT Experience

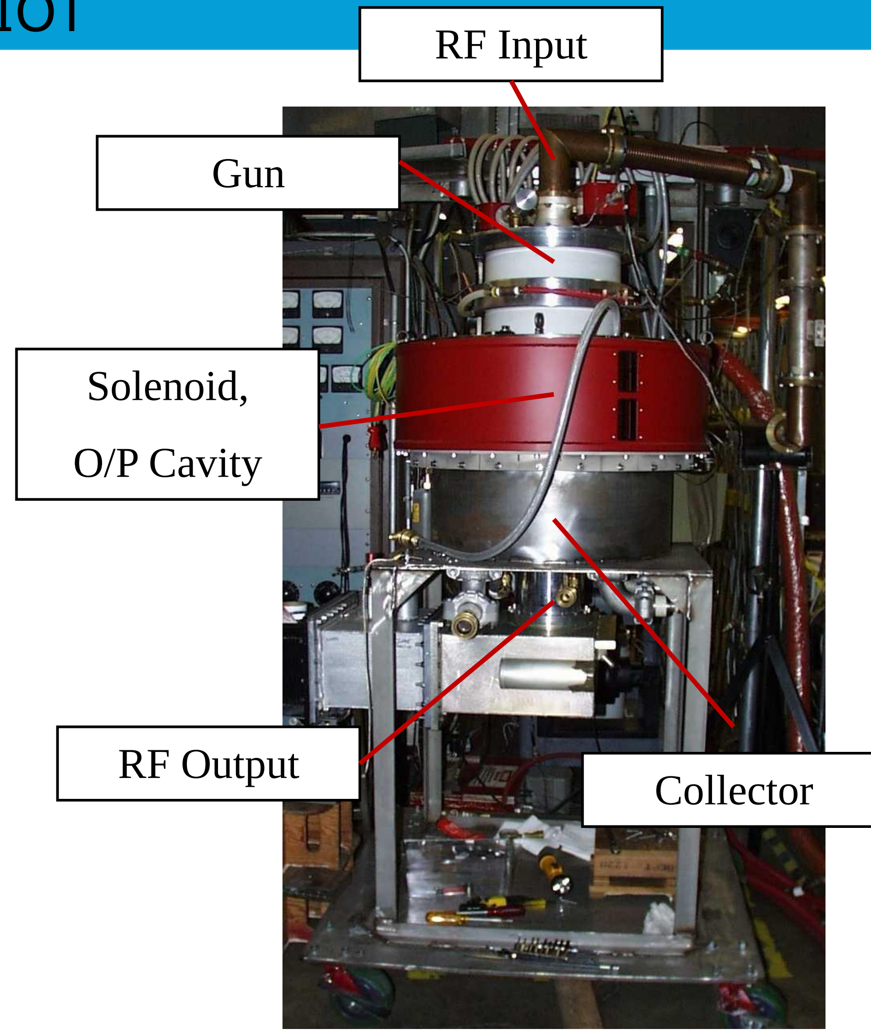
VHP-8330A IOT

Design Parameters

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



Test Results (pulsed)



CPI

IOT Advantages

Small

High Efficiency

Cost typically does not scale with output power

Low power consumption in standby or
for reduced output power

No pulsed HV

An IOT for ESS

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	

Target: Approval for ESS series production in 2017/18

Work is being carried out in collaboration with CERN

ESS to procure prototypes

CERN to make space and utilities available for testing

1.2 MW Multi-Beam IOT

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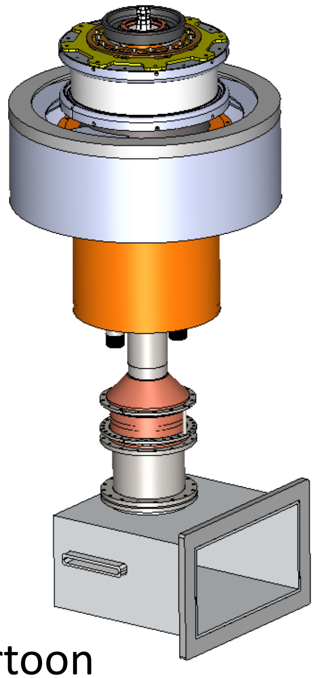
Contractual details sensitive due to active tender

- ESS launched tender for IOT prototypes
- Tender replies received and evaluation near complete
  - Several technical implementations received
- Order expected in the next couple of weeks
- Delivery in 24 months
- Site acceptance at CERN followed by long term soak test
- ESS > 3 MW saved from from high beta linac = 20 GWh per year

- Had hoped to present first work and pictures but can't yet.



CPI Cartoon

Thank You

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Is there interest from others in creating a special IOT interest group?