EUROPEAN SPALLATION SOURCE

Development of high-power IOTs as an efficient alternative to klystrons

Morten Jensen

Energy for Sustainable Science
24 October 2013, CERN

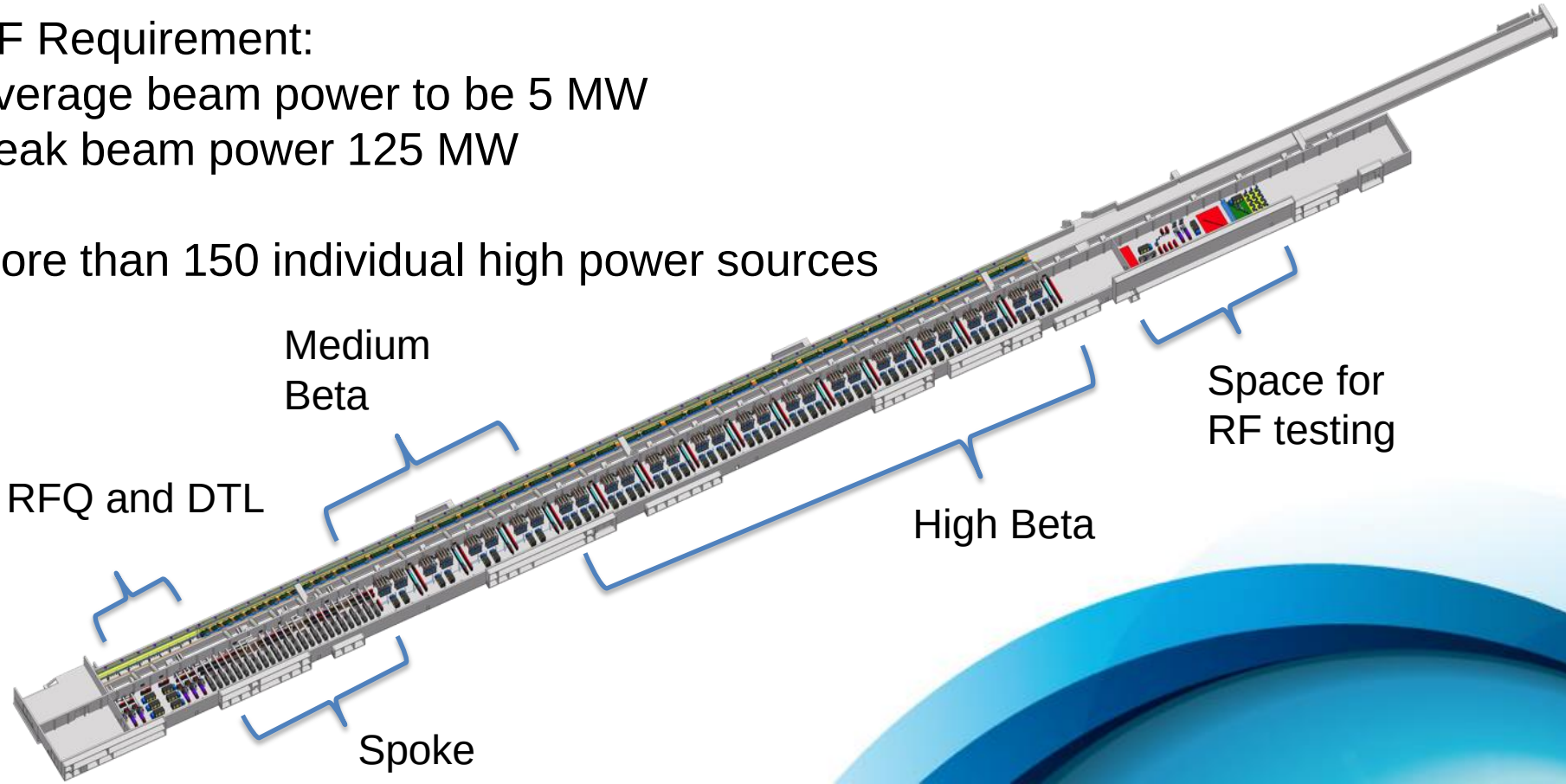
Overview

Will be the most powerful proton linac to date

- Energy: 2 GeV
- Beam current: 62.5 mA
- Pulse width 2.86 ms at 14 Hz

RF Requirement:
Average beam power to be 5 MW
Peak beam power 125 MW

More than 150 individual high power sources

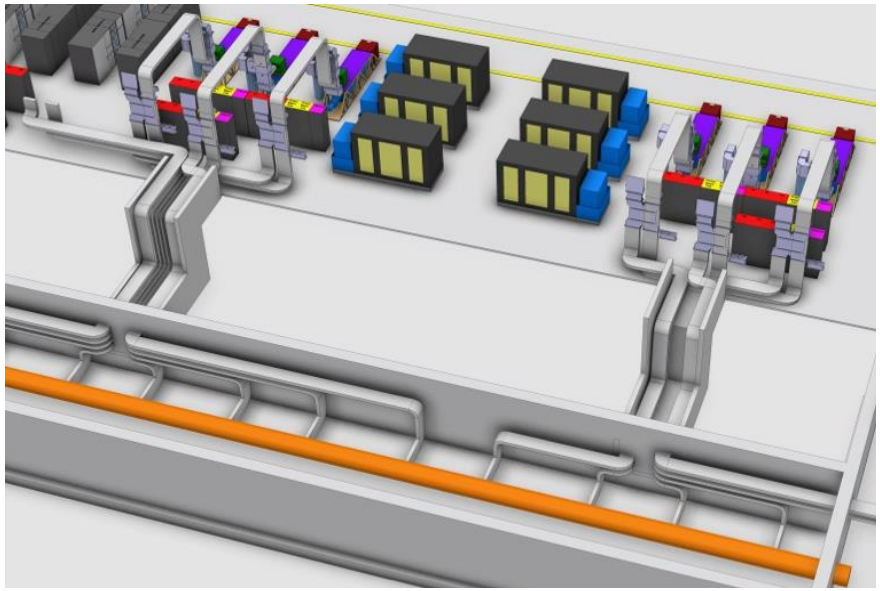


RFQ and DTL

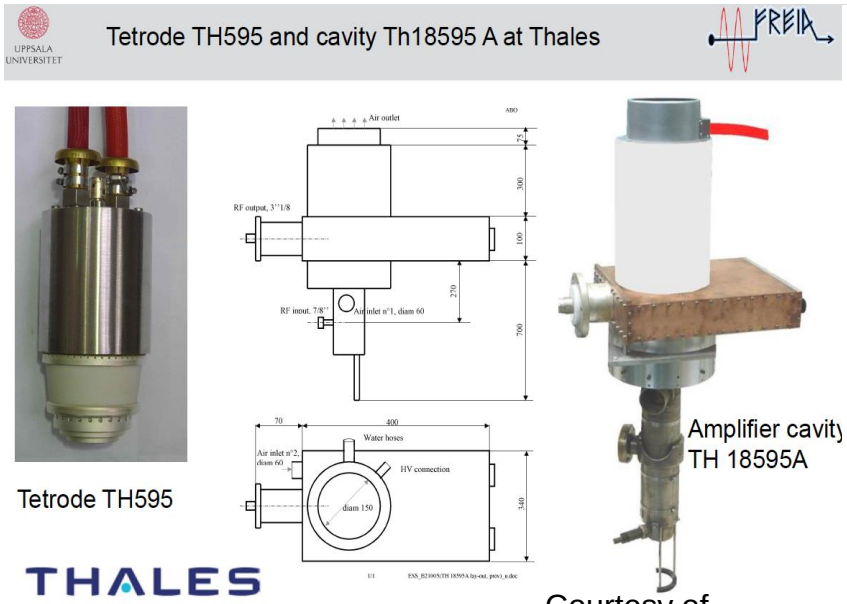
Five 2.8 MW klystrons for DLT
One 2.8 MW for RFQ

Power split to two couplers per DTL

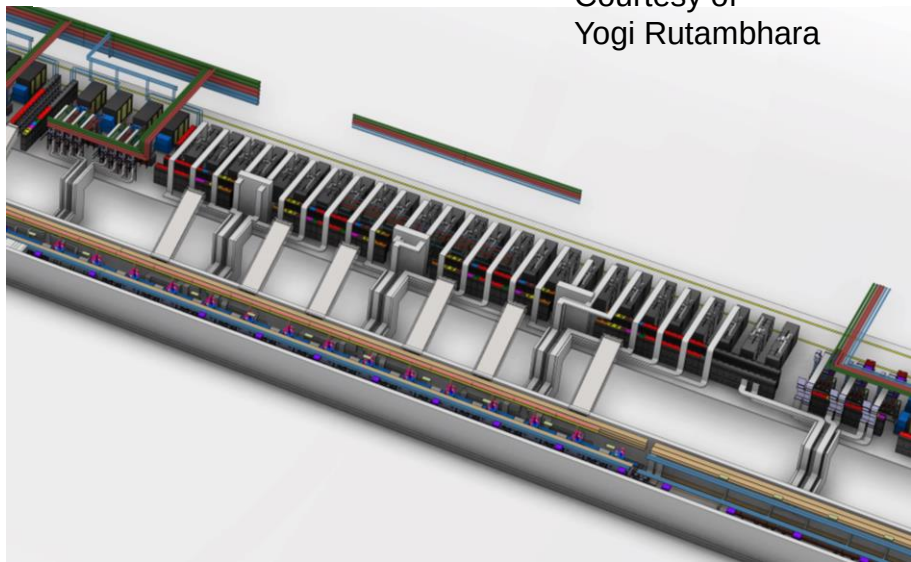
CPI	– VKP-8352B
Thales	– TH2179



Spoke Cavities



Courtesy of
Yogi Rutambhara



Cavities at 704 MHz

Two families of elliptical cavities

- 36 Medium Beta β_g = 0.67
  - 6 cell cavities
  - Maximum peak RF power = 850kW

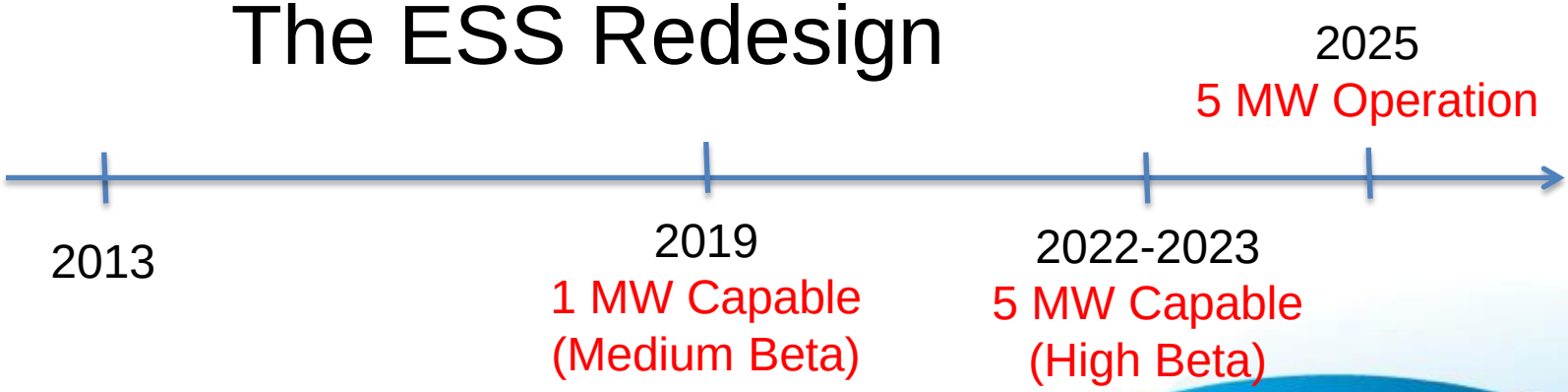
  Installation 2017-2019

- 84 High Beta β_g = = 0. 86
  - 5 cell cavities
  - Maximum peak RF power = 1100kW

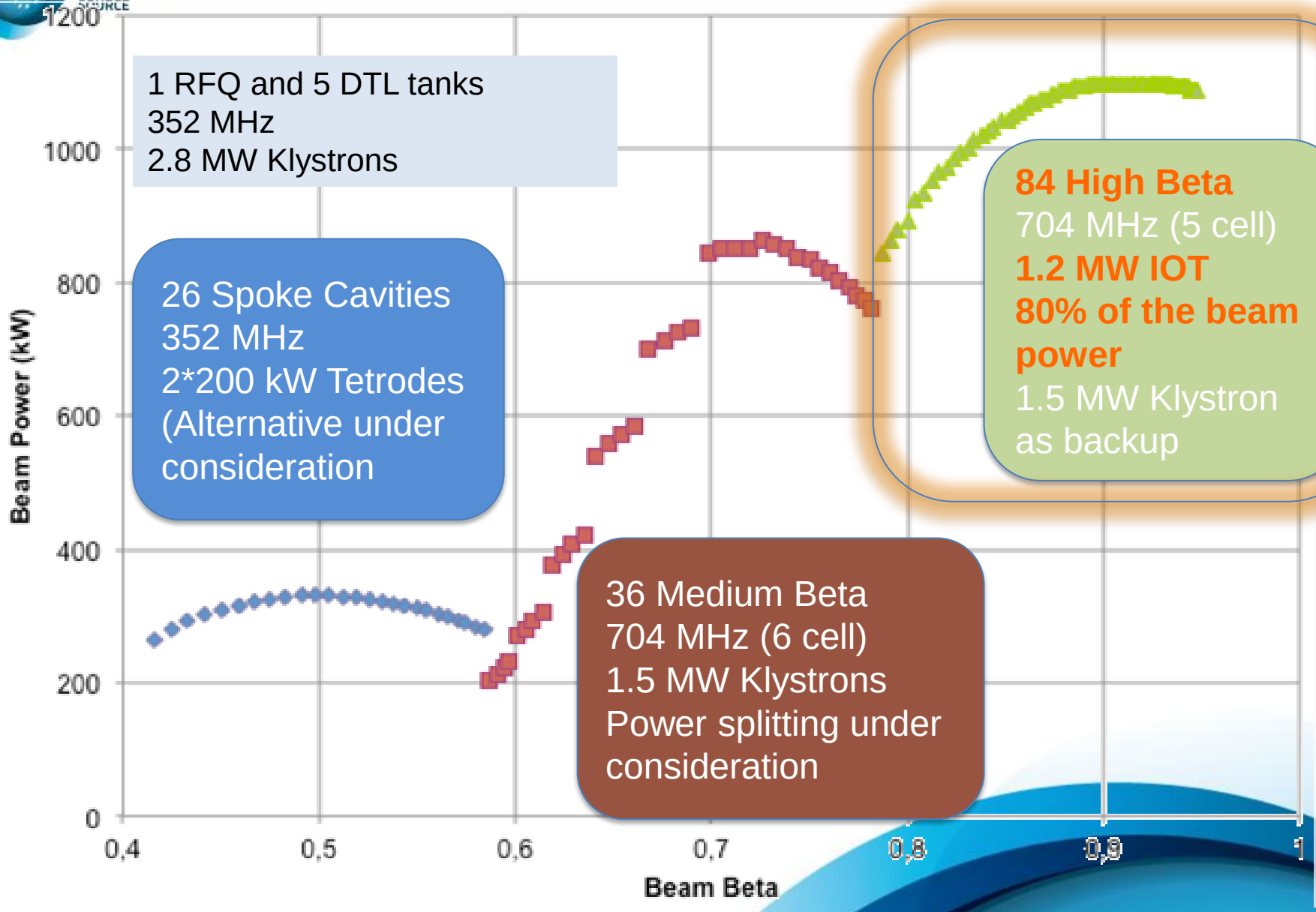
  Installation 2020-2023

Split installation phase means time to develop a new RF Source

The ESS Redesign



The ESS Superconducting Power Profile



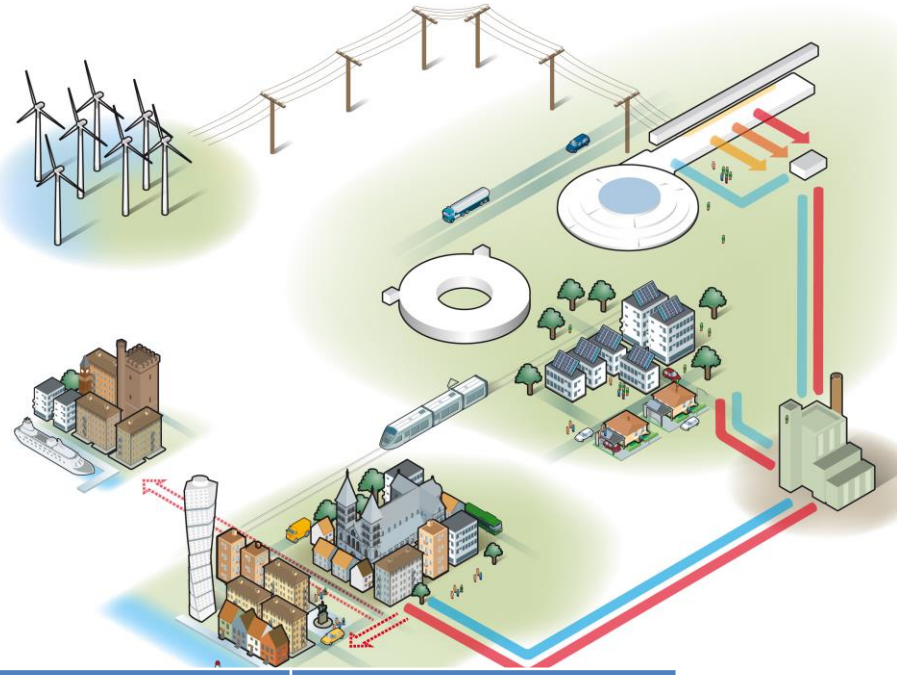
1 RFQ and 5 DTL tanks
352 MHz
2.8 MW Klystrons

26 Spoke Cavities
352 MHz
2*200 kW Tetrodes
(Alternative under consideration

84 High Beta
704 MHz (5 cell)
1.2 MW IOT
80% of the beam power
1.5 MW Klystron as backup

36 Medium Beta
704 MHz (6 cell)
1.5 MW Klystrons
Power splitting under consideration

The ESS Green Requirement



Carbon Neutral

Innovative

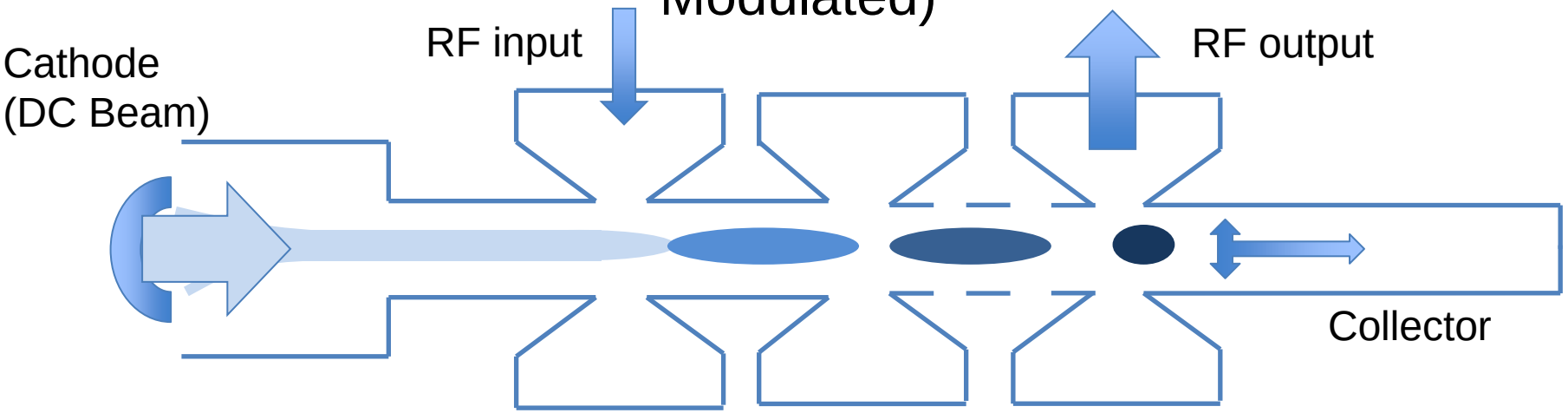
Green

Accelerating Structure	Freq. (MHz)	Quantity	Max Power (kW)
RFQ, DTL	352	6	2200**
Spoke	352	26	240**
Elliptical Medium Beta	704	36	800**
Elliptical High Beta	704	84	1100**

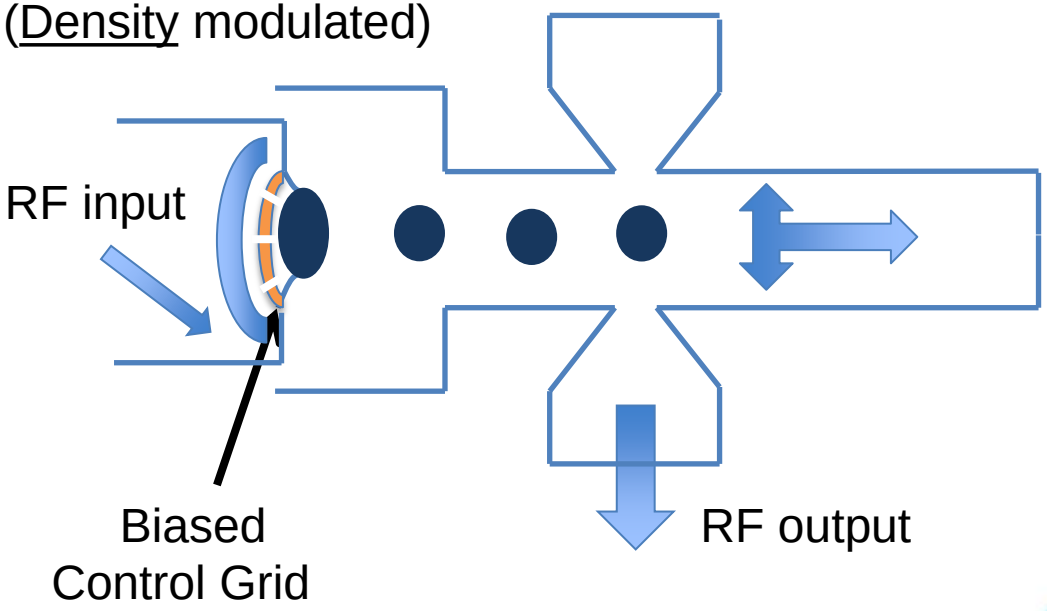
Target highest efficiency devices at high power end

** Plus overhead for control

Klystron (Velocity Modulated)



IOT
(Density modulated)



Reduced velocity spread
- Higher efficiency

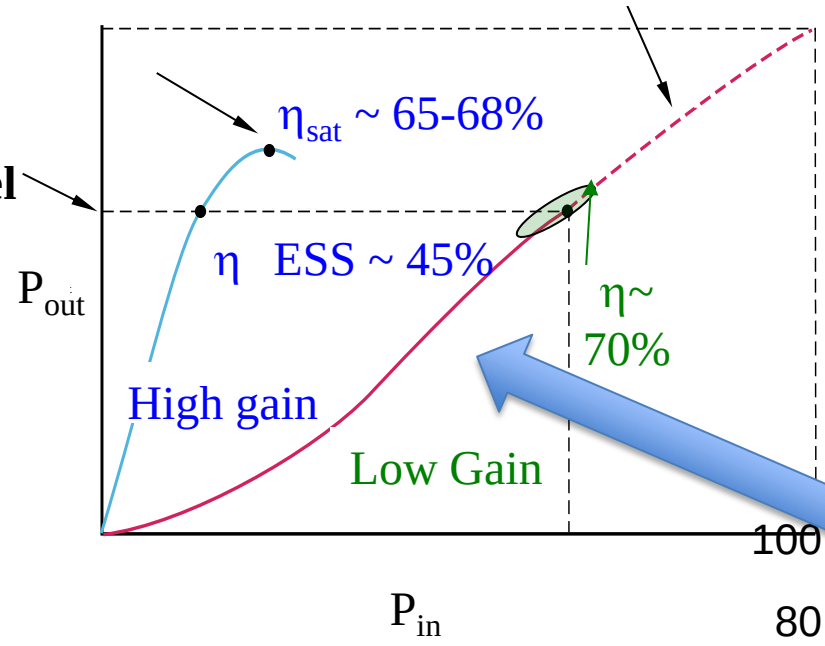
No pulsed high voltage
- Cheaper modulator

The Performance Comparison

IOT's don't saturate.
Built-in headroom for feedback.

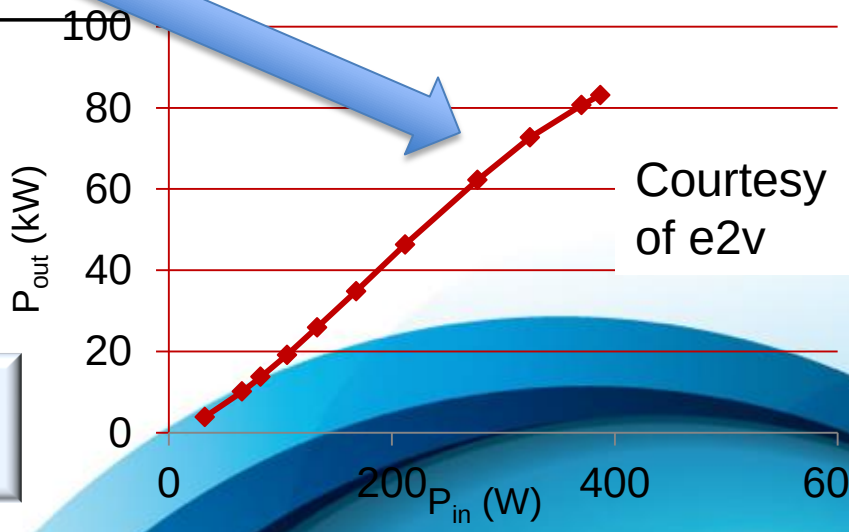
Klystron/MBK

IOT
MB-IOT



Courtesy of CPI

Typical Example of 80 kW IOT
Tuned for 80 kW @ 36 kV



Courtesy of e2v

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

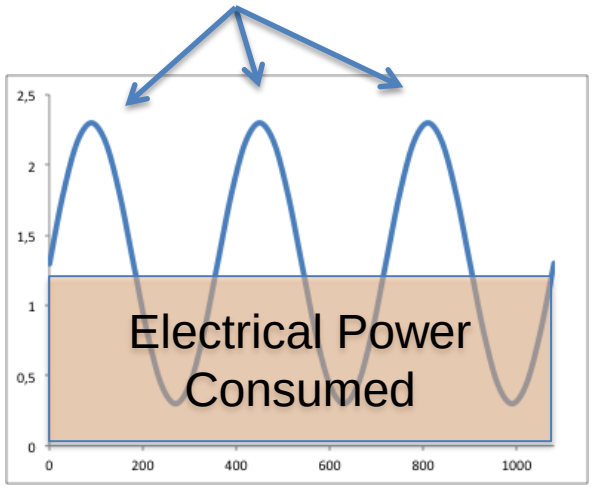
Klystrons

IOTs

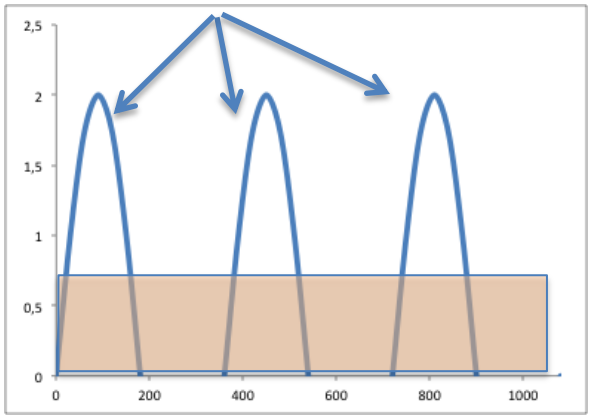
Power delivered to beam

Cartoon!

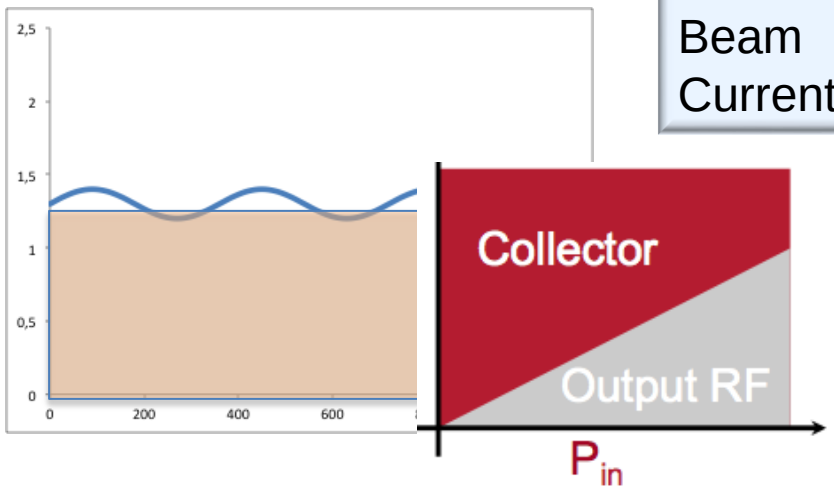
Power delivered to beam

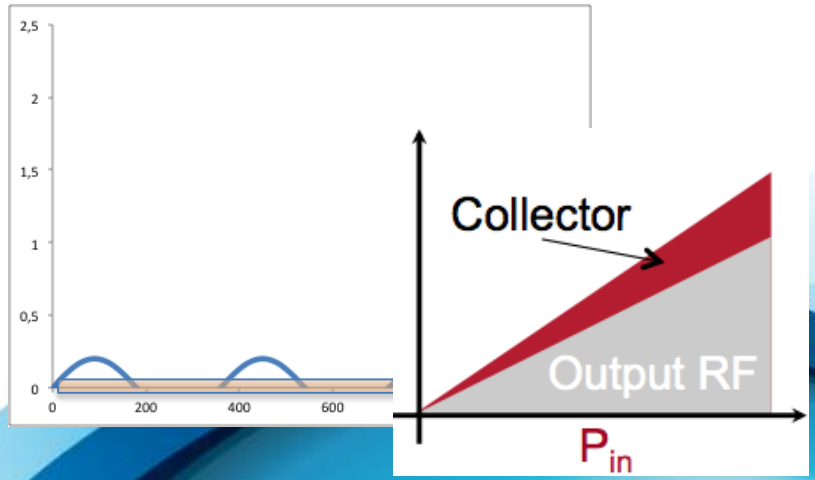


High Beam Current



Low Beam Current





IOT Advantages

Significantly smaller than a klystron

High efficiency at operation point

Cost typically does not scale strongly with output power

- Advantage at high power compared to Solid State Amplifiers

Low power consumption in standby or for reduced output power

No need to pulse HV for pulsed operation

Broadcast Industry has promoted IOT development
Klystrons have almost been replaced

Key enabling developments:
Pyrolytic Graphite
Solid State Drivers

Power levels limited to approximately 90 kW CW 150 kW pulsed

ESS to push the technology to MW levels

High Development Cost is prohibitive for many smaller accelerators

High requirement justifies R&D development for ESS parameters

Successful development will reduce risk for variants for other accelerators

Selection of Laboratories already 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 …

What would it mean for ESS?

High Efficiency and Minimal Energy Consumption is Mandatory for ESS

- Modulator Efficiency 90% to > 95%
- RF Efficiency 43% to > 60%
- Power Saving from High Beta section 3.3 MW
- Lower voltage, no oil tanks
- Heat from collectors can still be recovered
- Modulator capital cost is lower saving 6-10 M EUR
- Smaller form factor affecting space/cost of the building

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

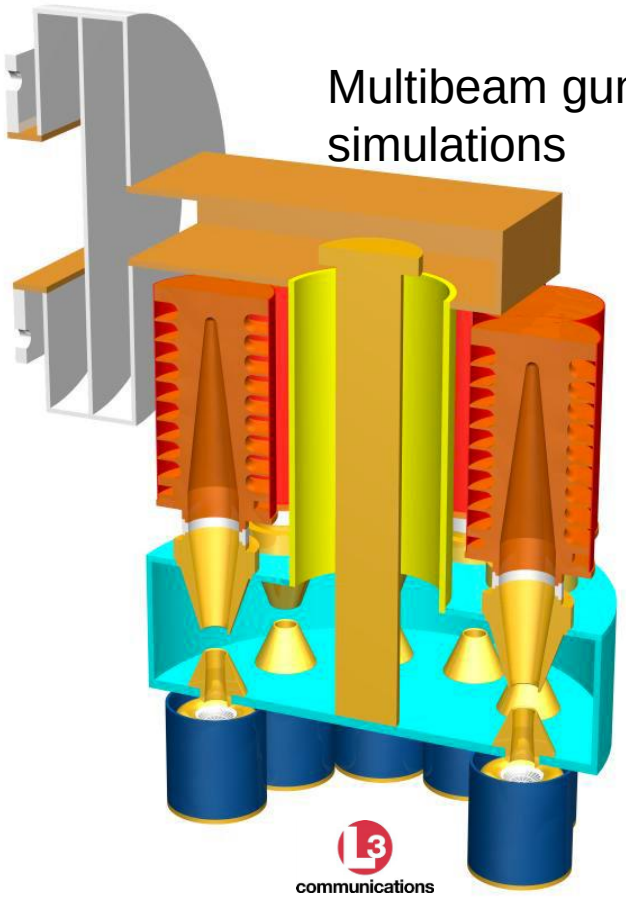
- Single beam high power IOT
  - High voltage gun (> 90 kV)
  - Large cathode for low charge density
  - High voltage modulator design

- **Multi-Beam IOT**
  - **Reduced high voltage (< 50 kV)**
  - **Low space charge per beam**
  - **Very compact**
  - **High efficiency**

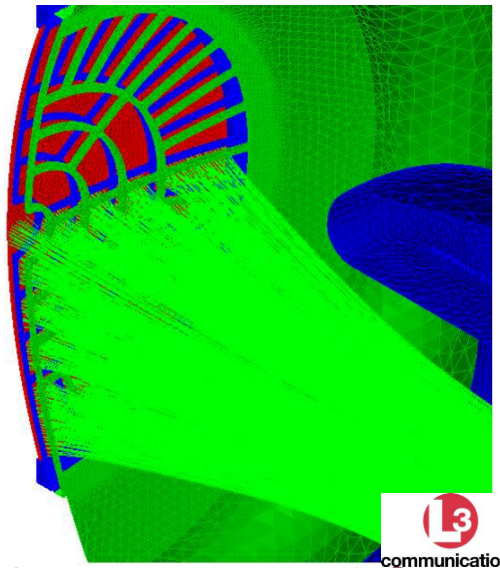
Typical components

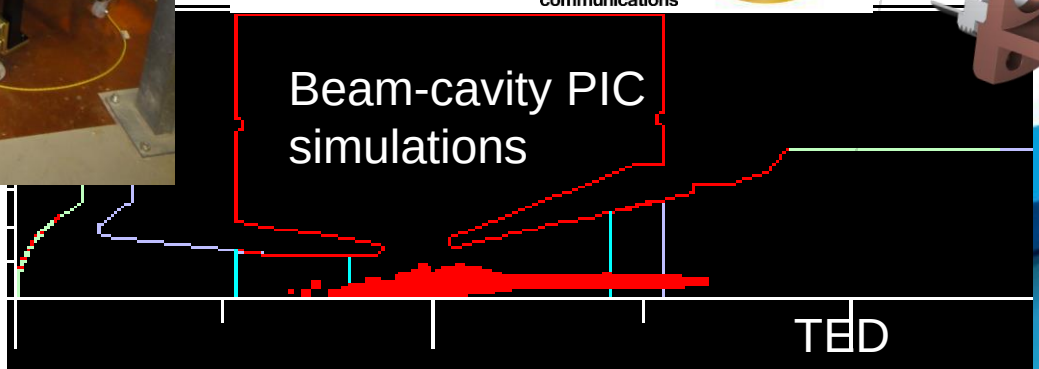
IOT installation at Diamond Lights Source

e2v



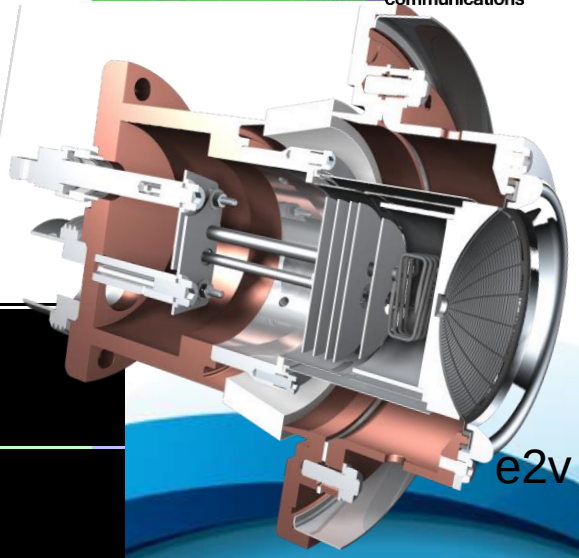
Multibeam gun simulations





Beam-cavity PIC simulations

TED



e2v

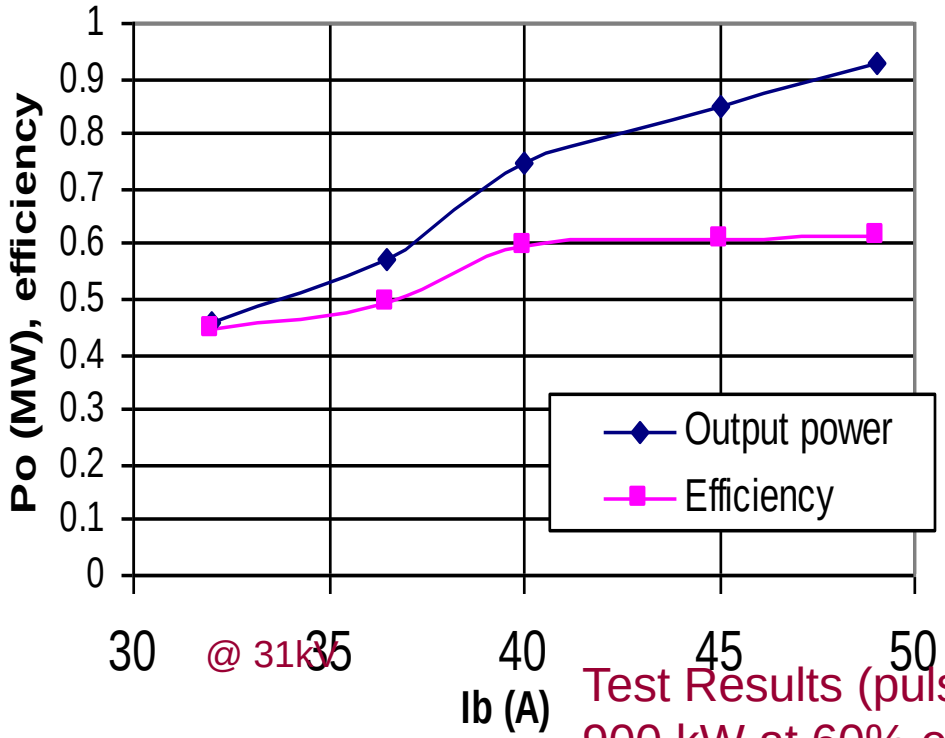
Typical single beam gun

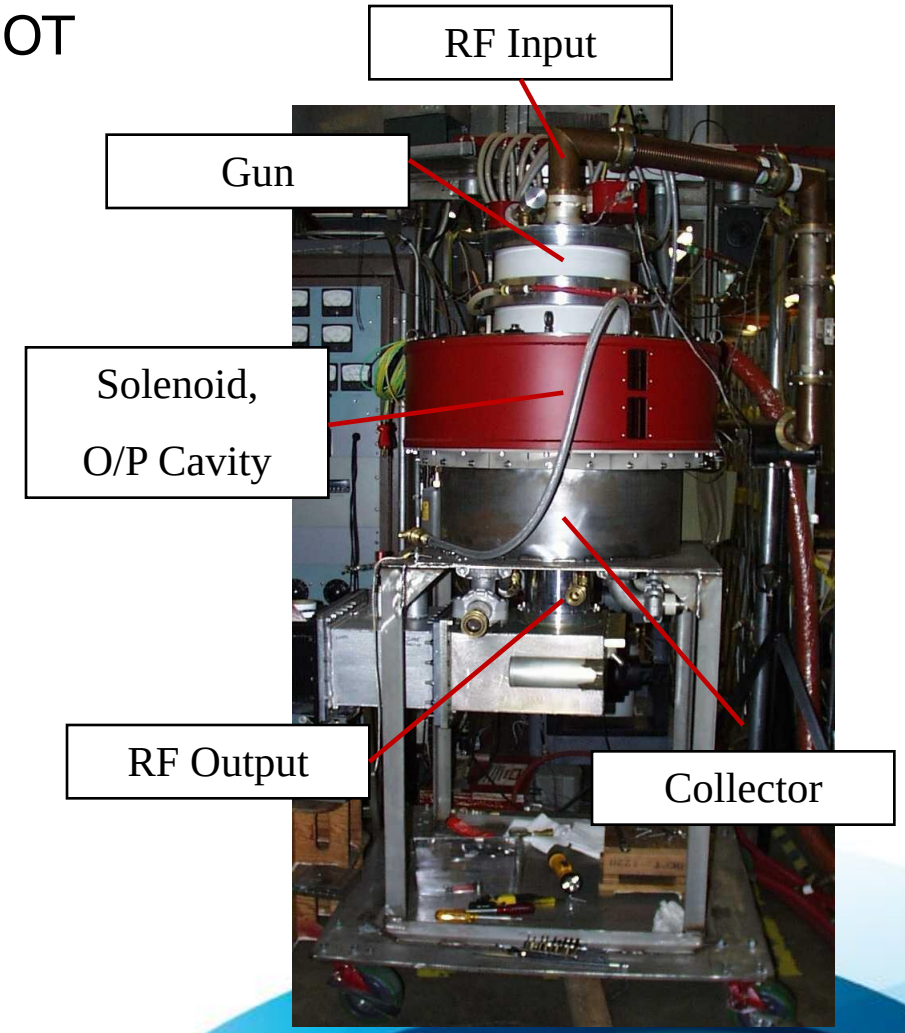
700 MHz HOM IOT Experience

CPI

VHP-8330A IOT

Design Parameters	value	units
Power Output	1000	kW (min)
Beam Voltage	45	kV (max)
Beam Current	31	A (max)
Frequency	700	MHz
1dB Bandwidth	± 0.7	MHz (min)

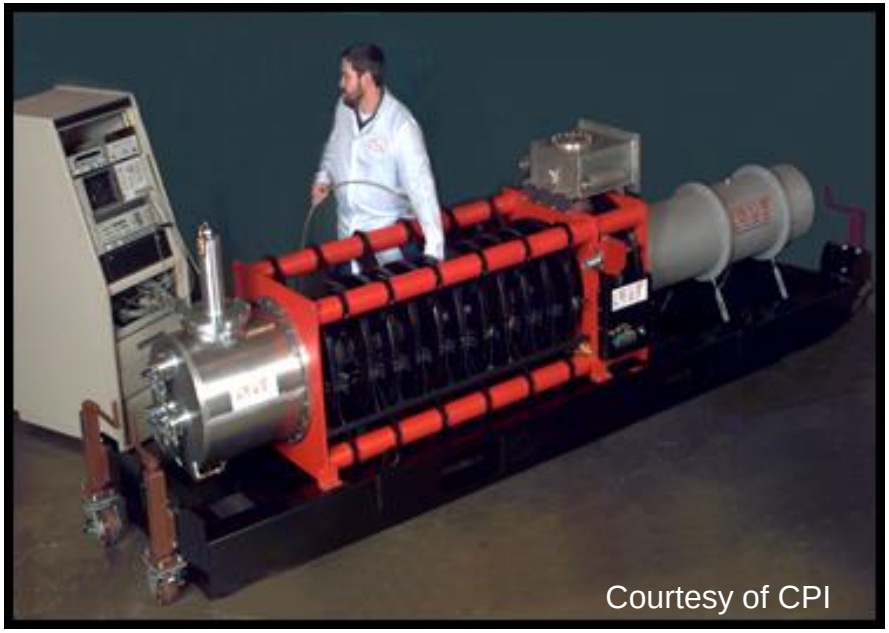


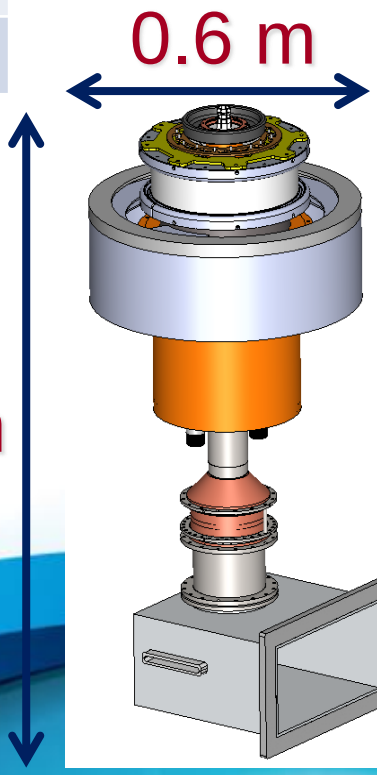


Test Results (pulsed)
900 kW at 60% efficiency

A 700 MHz Klystron – IOT Comparison

	Single Beam Klystron	MB IOT	
Peak output Power	1	1	MW
Cathode Voltage	95	50	kV
Efficiency at saturation	65	65 (min)	%
Est. efficiency for operation	<45	>60	%
Gain	48	23	dB

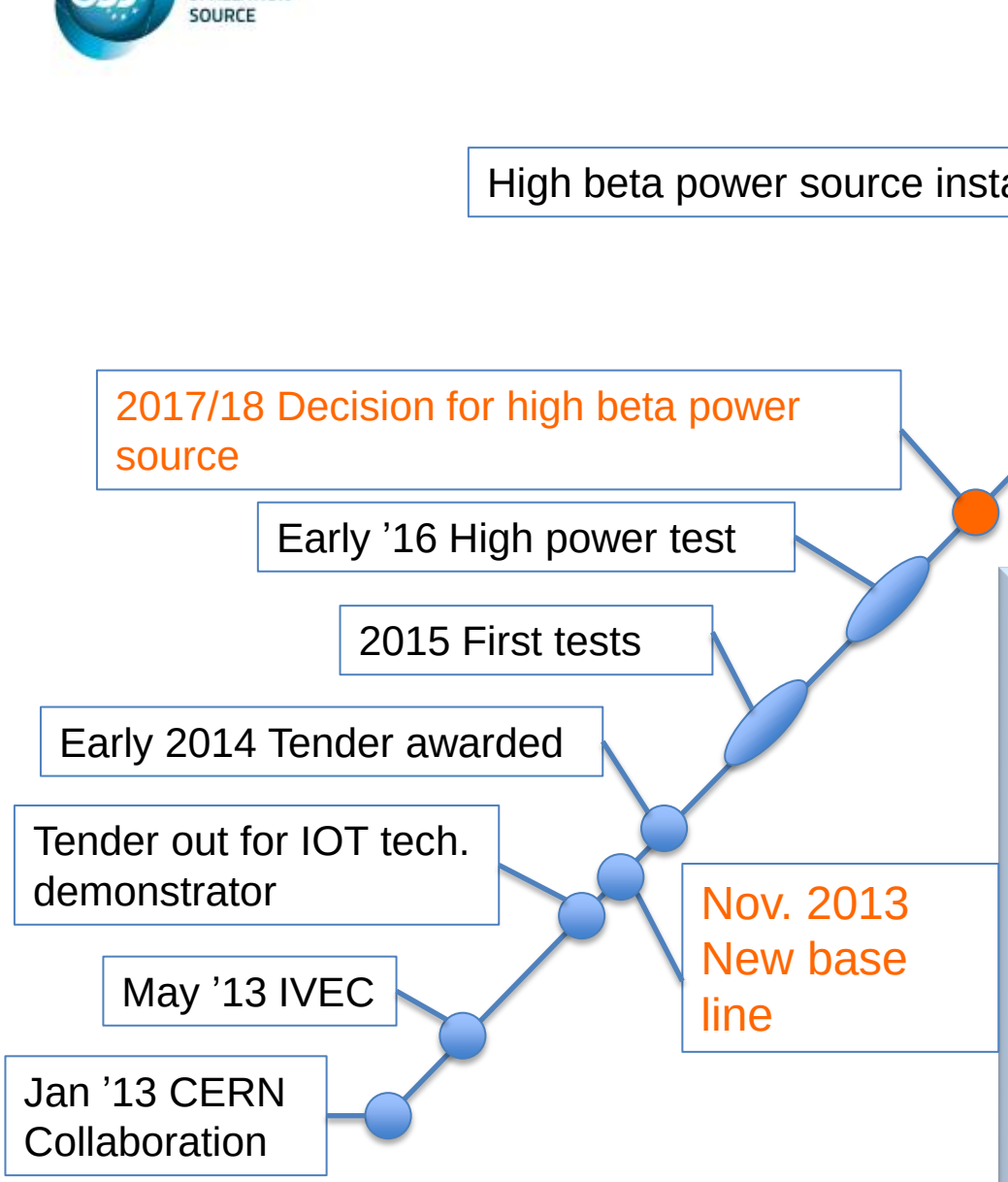




Target IOT Parameters for Prototype Build

Parameter		Comment
Frequency	704 MHz	
Maximum Power	1.2 MW	During pulse plus overhead for regulation
Pulse length	Up to 3.5 ms	Beam pulse 2.86 ms
Pulse repetition freq.	14 Hz	Duty factor 5%
Gain	> 20 dB	
Overhead margin	30%	Short duration only
High voltage	< 50 kV	No oil for the PSU nor the gun tank
Efficiency at 1.2 MW	≥ 65%	Design target
Design lifetime	50,000 hrs	Design target comparable with klystrons
Grid bias / Idle current	No idle current between pulses	May be gated
Prototypes required	2	Preference for two separate manufacturing sites
Series production	84	Plus initial 10% spares, plus ongoing supply

Schedule Considerations



Original plan:

- Use the same klystron for medium and high beta
- 704 MHz klystron prototype nearly ready – ‘safe’ backup
- Modulator development in parallel
- **Financial rather than project risk but cost recovered in operation**

Summary

- ESS will deliver an innovative Green Accelerator with high efficiency devices
- ESS RF requirement is huge
- ESS offers a Unique Opportunity to Develop and Deliver State of the Art Technology
- The IOT Development Represents No Project Risk to ESS with a Proven and Mature Technology Backup
- Cost of IOT prototype recovered in < 2 years operation on top of the initial capital cost saving on modulators