

# High Power RF Sources for the ESS RF Systems

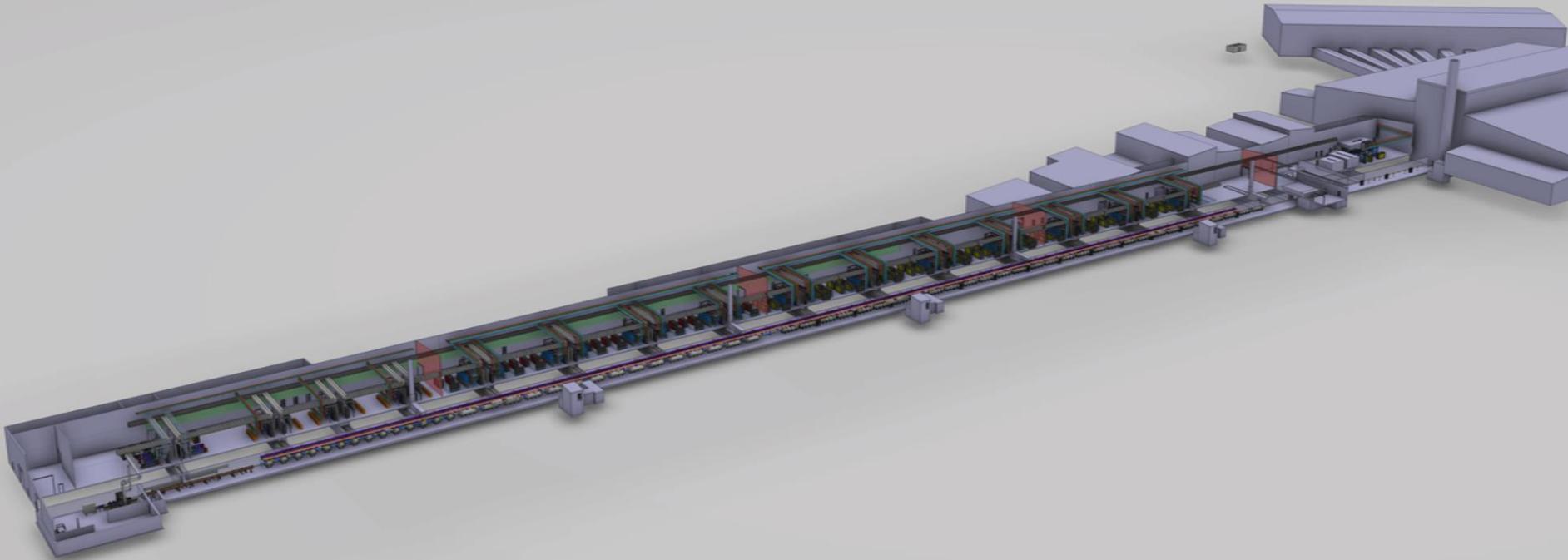
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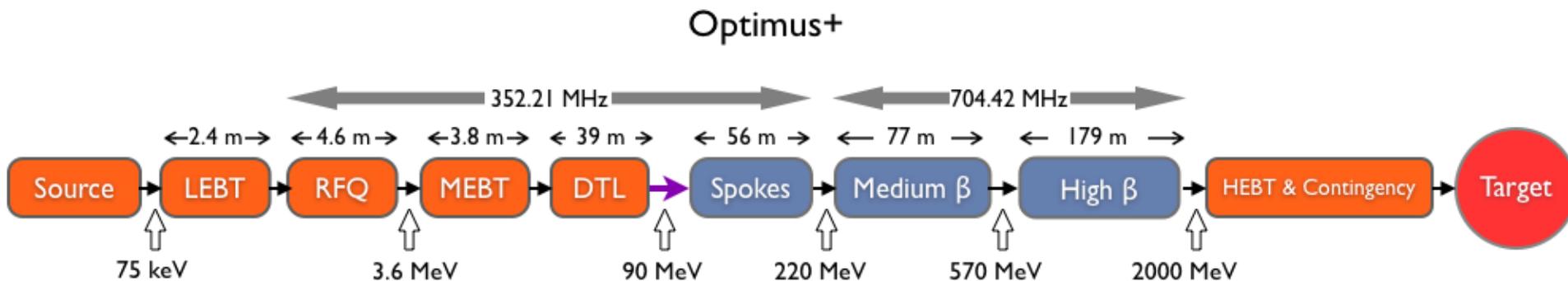
# Agenda

- Introduction to ESS
- Power profile and Technology Choices
- IOTs



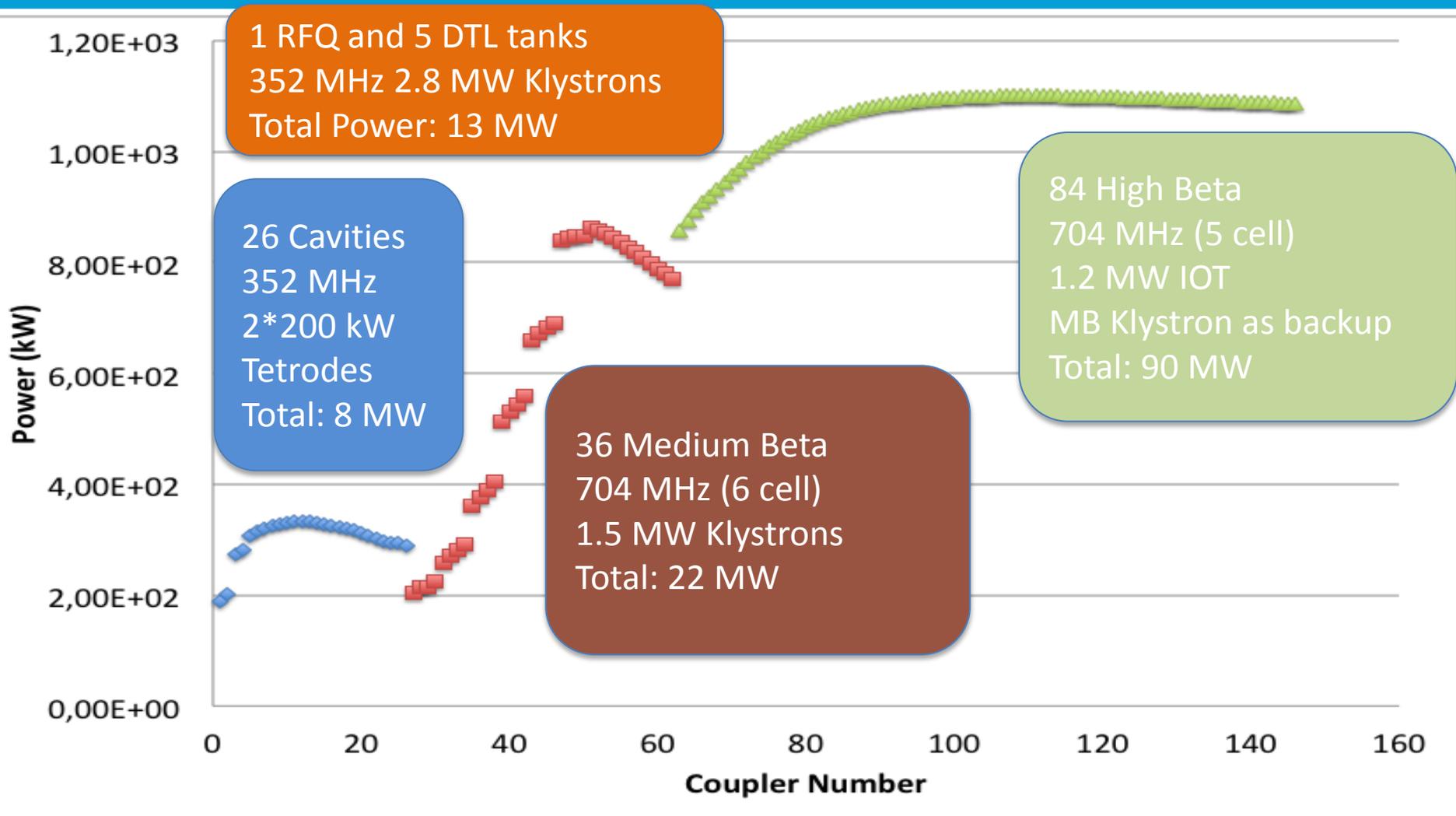
# Linac Design Choices

- User facilities demand high availability (>95%)
- The linac will be mostly (>97%) superconducting
- Front end frequency is **352 MHz** (CERN Standard)
- High energy section is at **704 MHz**
- ESS will limit the peak beam current below **62.5 mA** (was 50 mA)
- Linac Energy of 2 GeV - **125 MW** peak power.



# The ESS Superconducting Power Profile

> 150 cavities/couplers



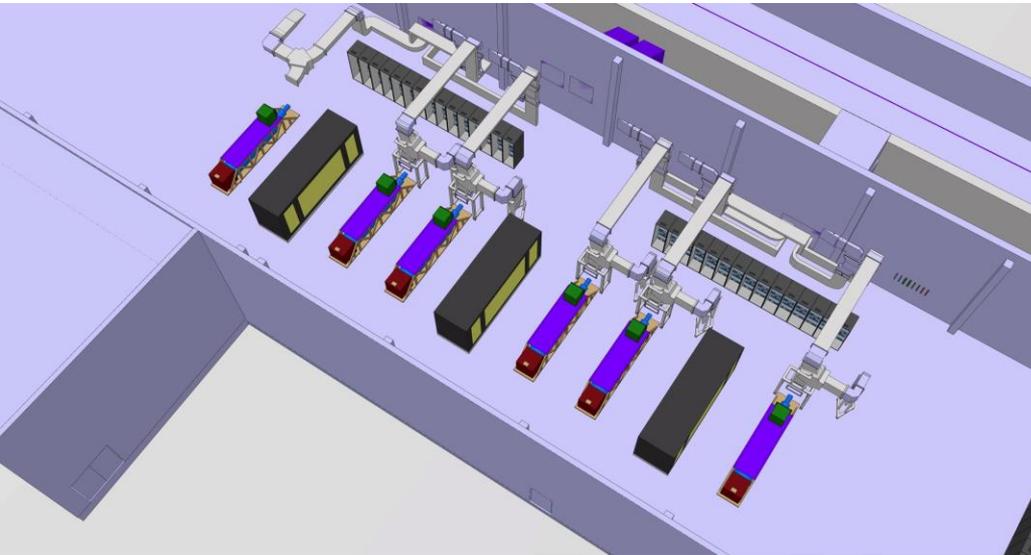
**Total High Power RF: 133 MW peak (4% duty) plus overhead**

# RF distribution for the RFQ and 5 DTLs Layout being finalised

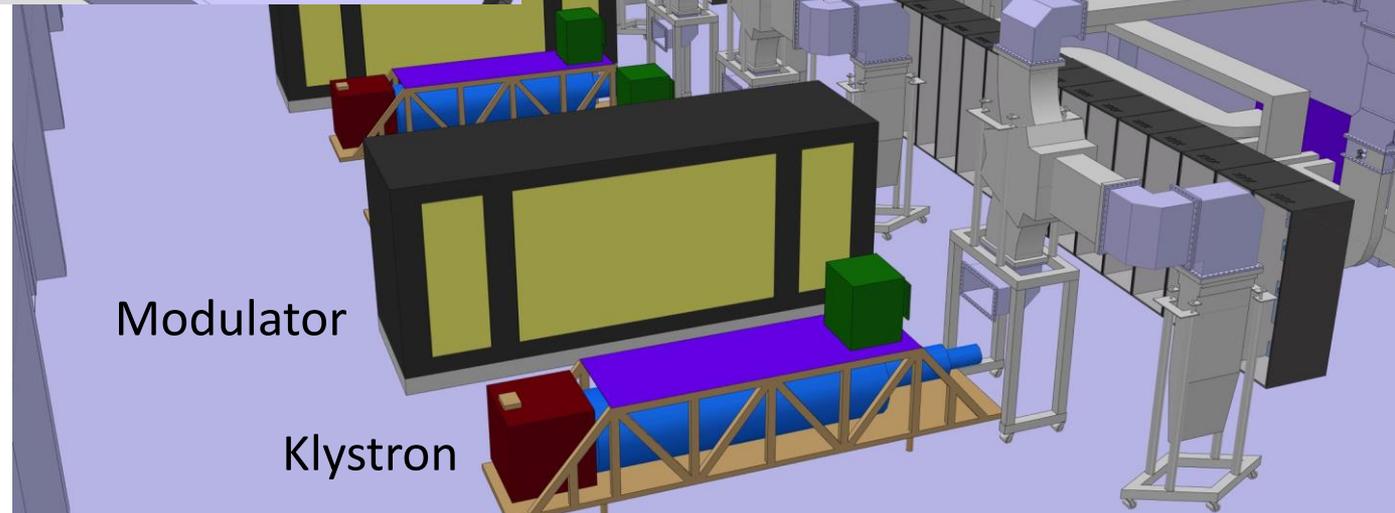
One 2.8 MW for RFQ  
Five 2.8 MW klystrons for DLT

Power split to two couplers per DTL tank

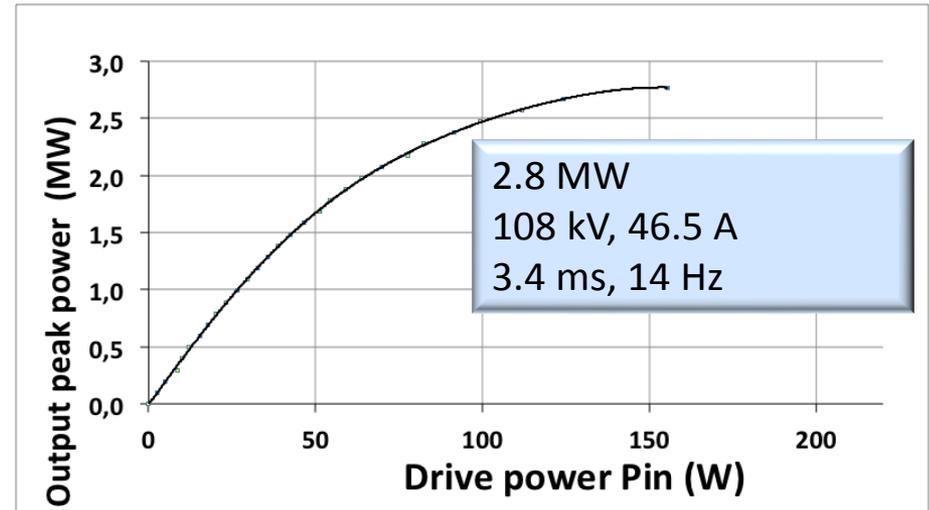
|        |             |
|--------|-------------|
| CPI    | – VKP-8352B |
| Thales | – TH2179    |



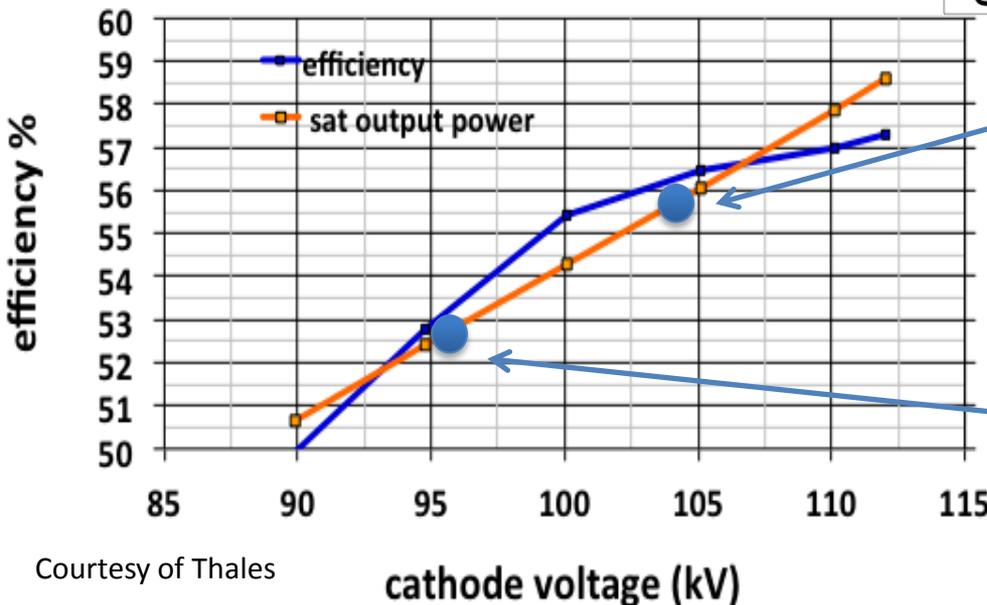
2 Klystrons per  
modulator



# Possible RFQ and DTL Power Source



Investigating option to operate at lower voltage for lower power operation



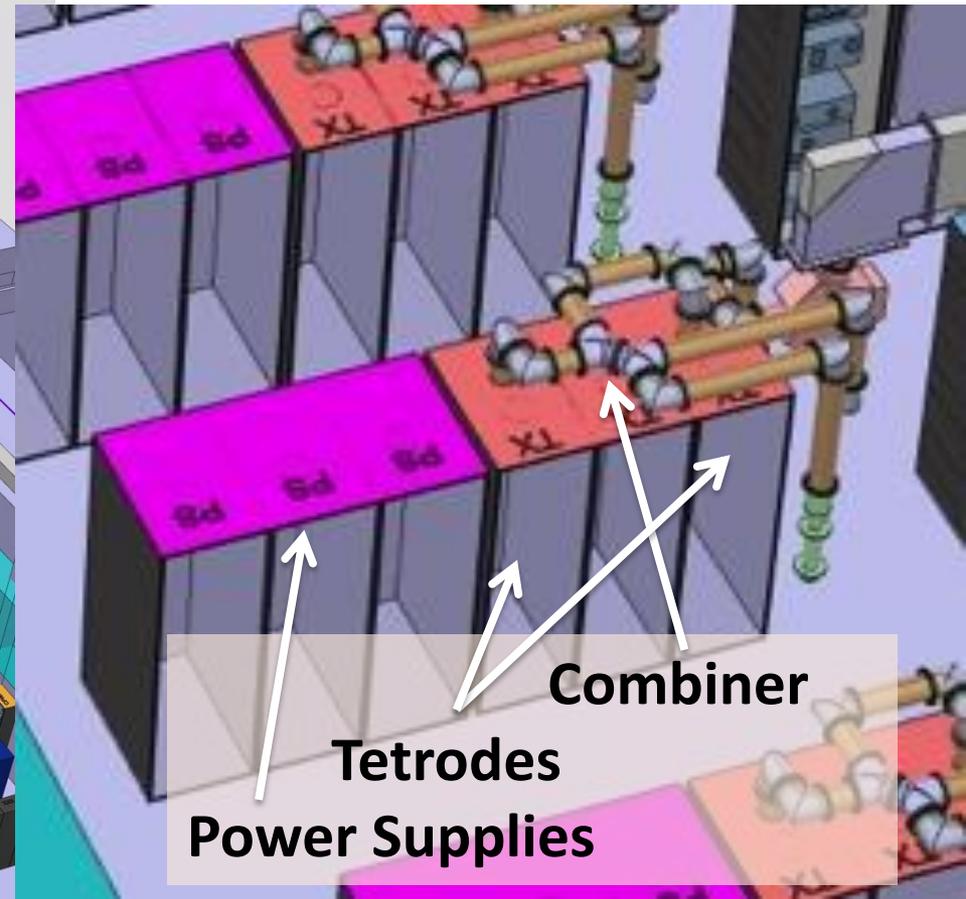
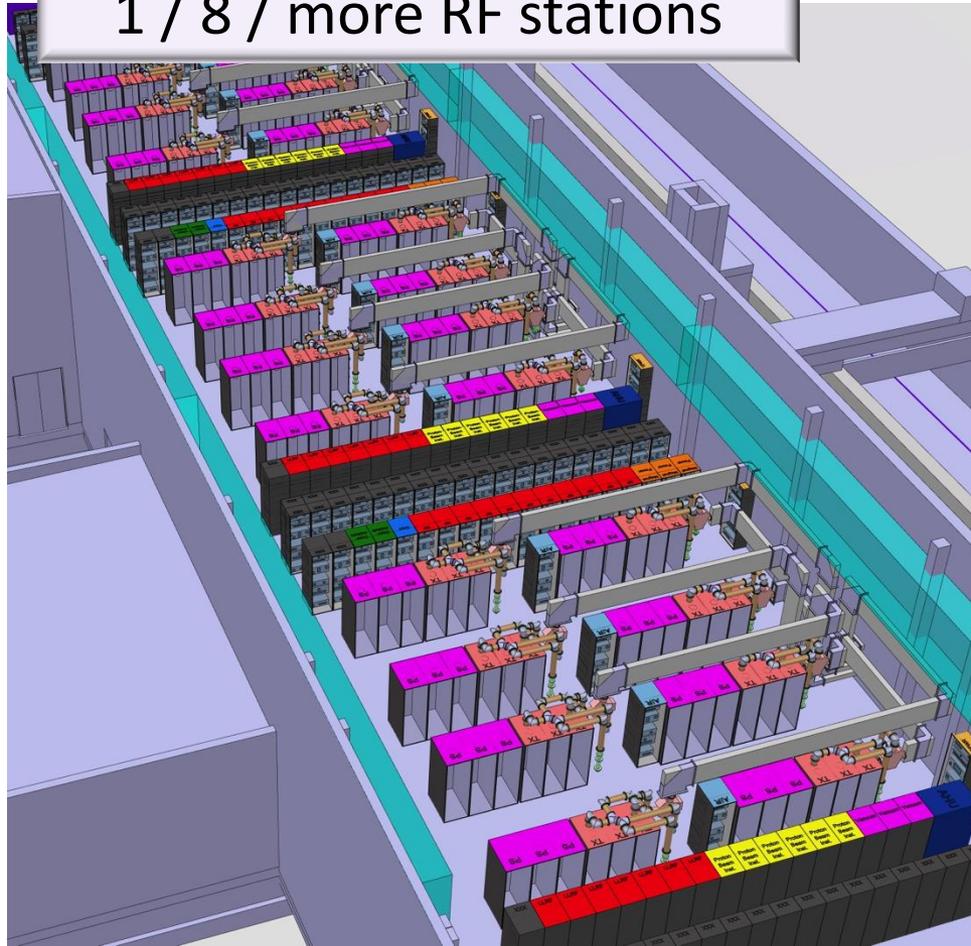
DTL:  
Saturation efficiency = 55%  
Beam efficiency = 46%  
Full voltage efficiency = 41%

RFQ:  
Saturation efficiency = 52%  
Beam efficiency = 43%  
Full voltage efficiency = 31%

# Spoke linac (352 MHz) RF System Layout

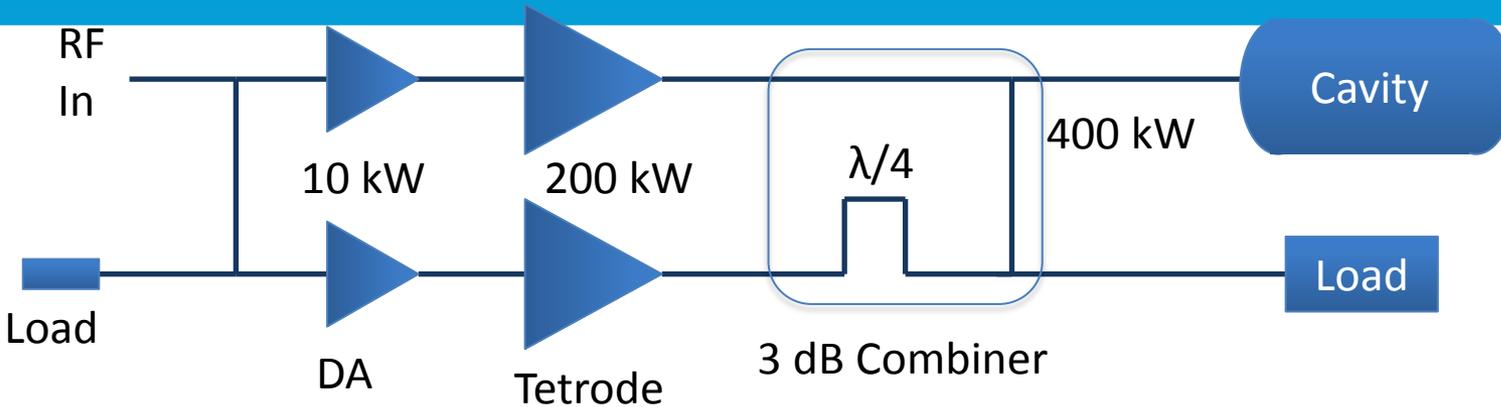
## Conceptual Only

26 Double Spoke cavities  
Considering: 1 PSU per  
1 / 8 / more RF stations



# Spoke linac RF System

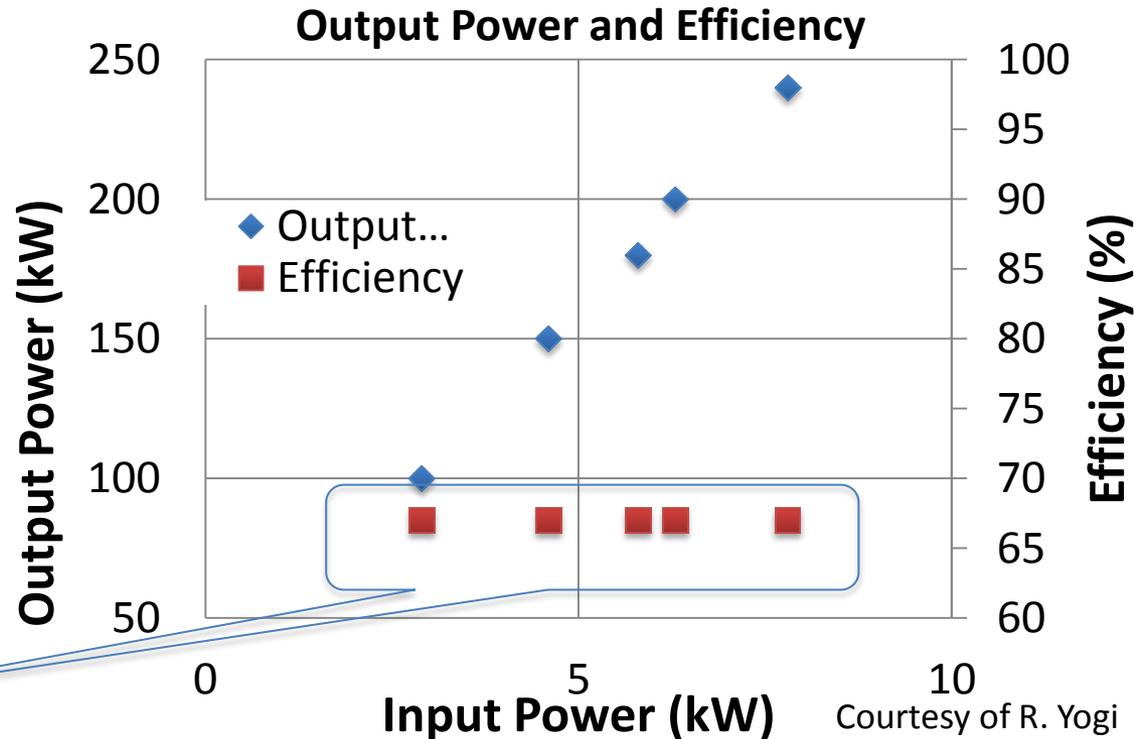
TH595 Tetrode



Individual or common (tetrode) driver  
Circulator under consideration

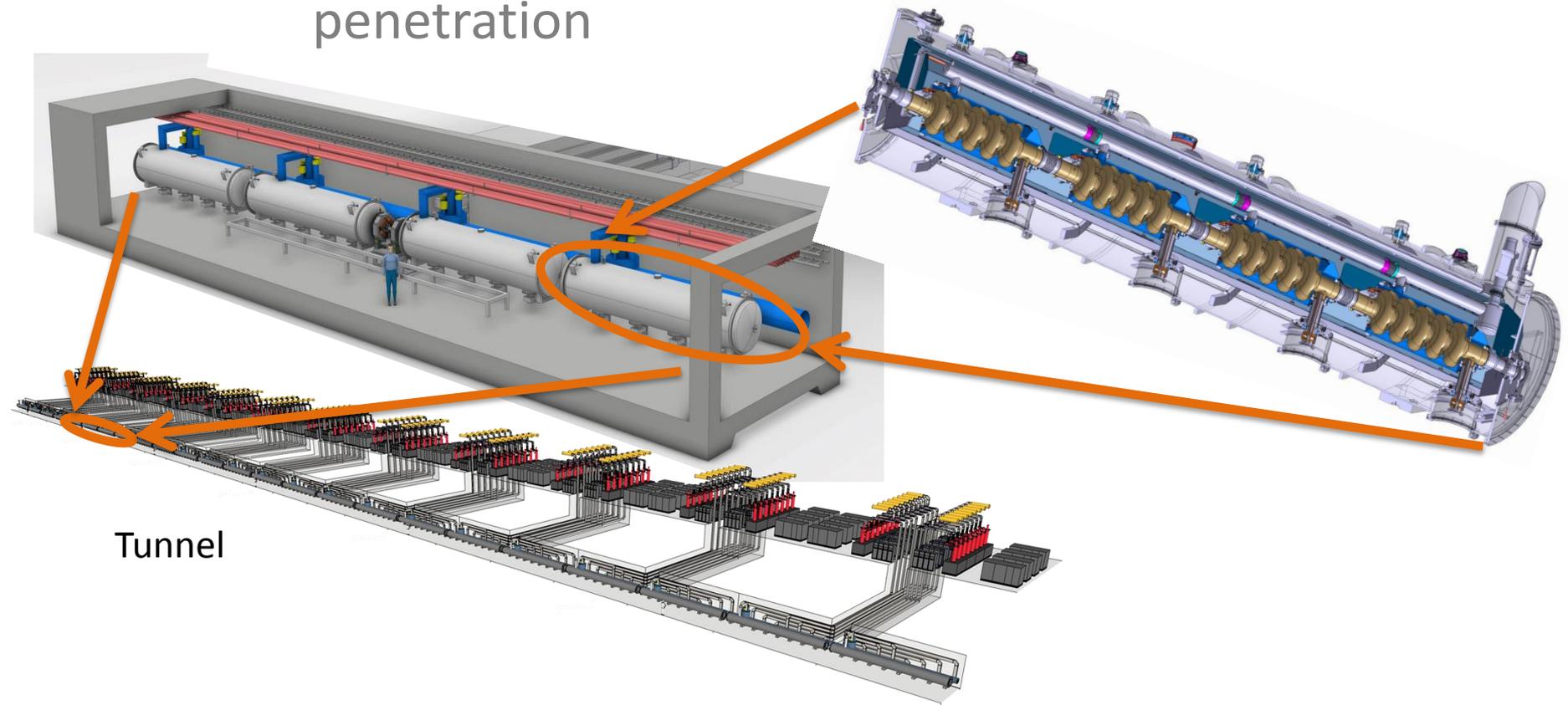
High efficiency at point of operation  
Margin for overhead

Anode efficiency > 65%  
at all power levels



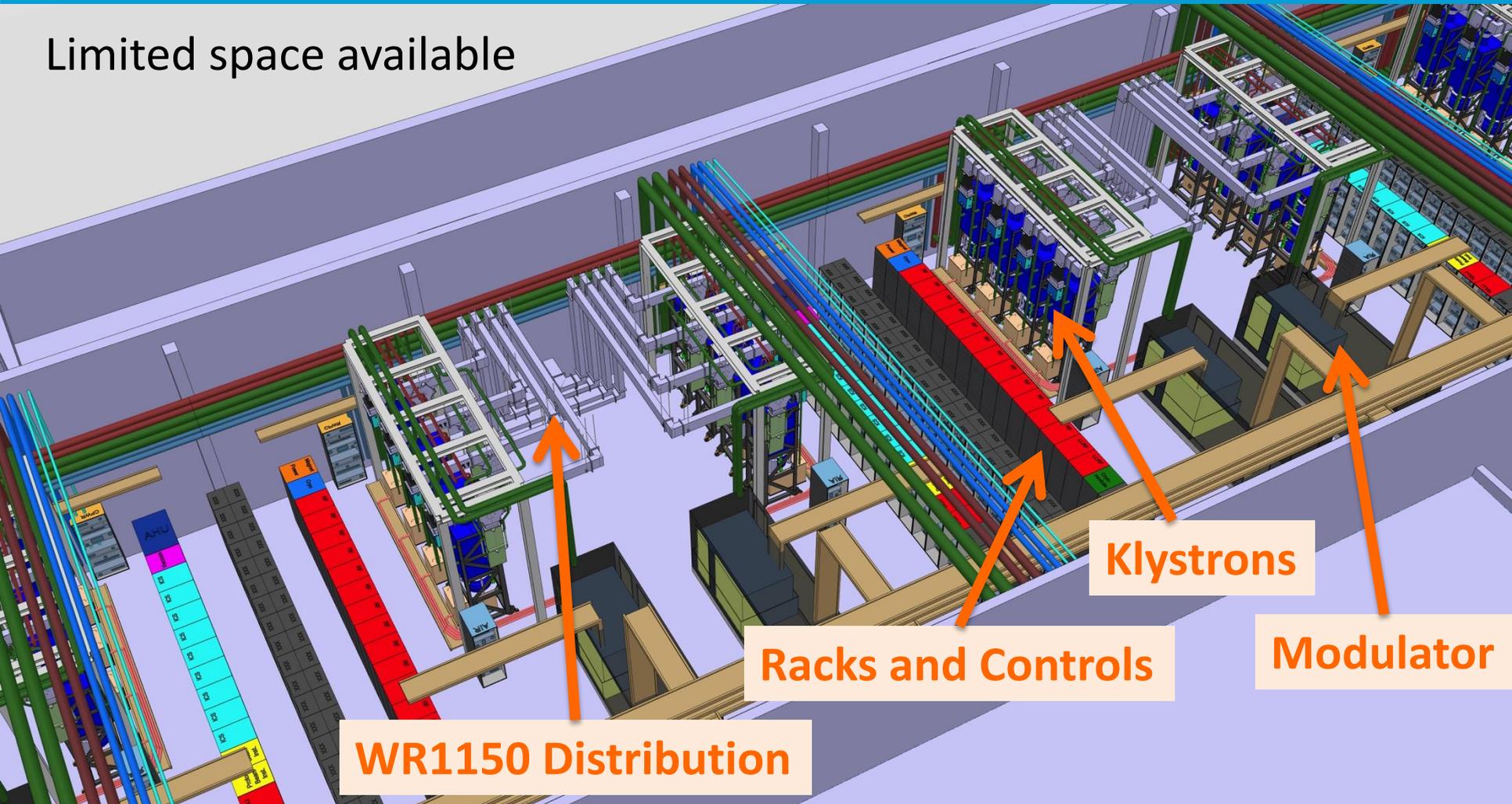
# Elliptical (704 MHz) RF System Layout

- One cavity per klystron
- 4 klystrons per modulator
- 16 klystrons per tunnel penetration



# Elliptical (704 MHz) RF System Layout

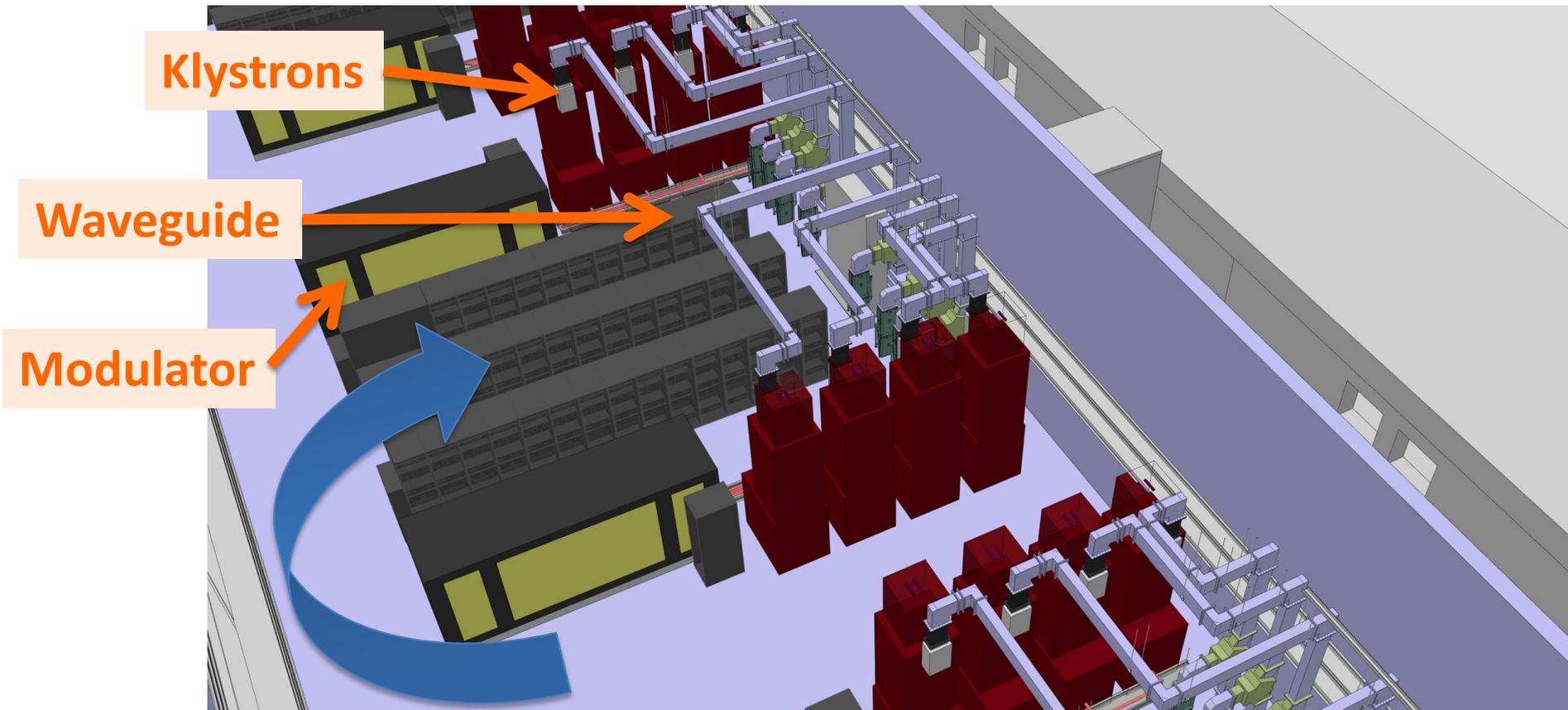
Limited space available



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

# Elliptical (704 MHz) RF System Layout

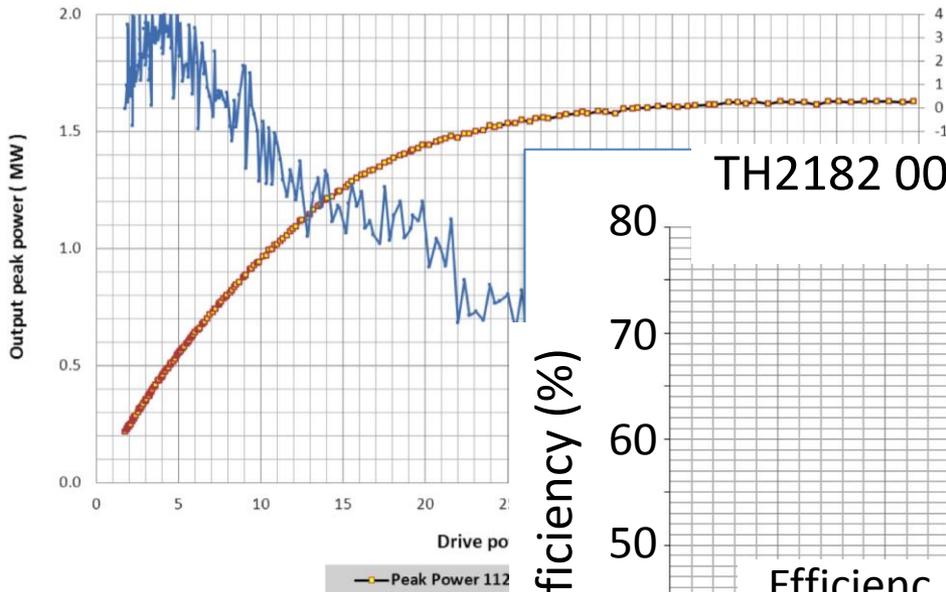
(but last week it may have changed)



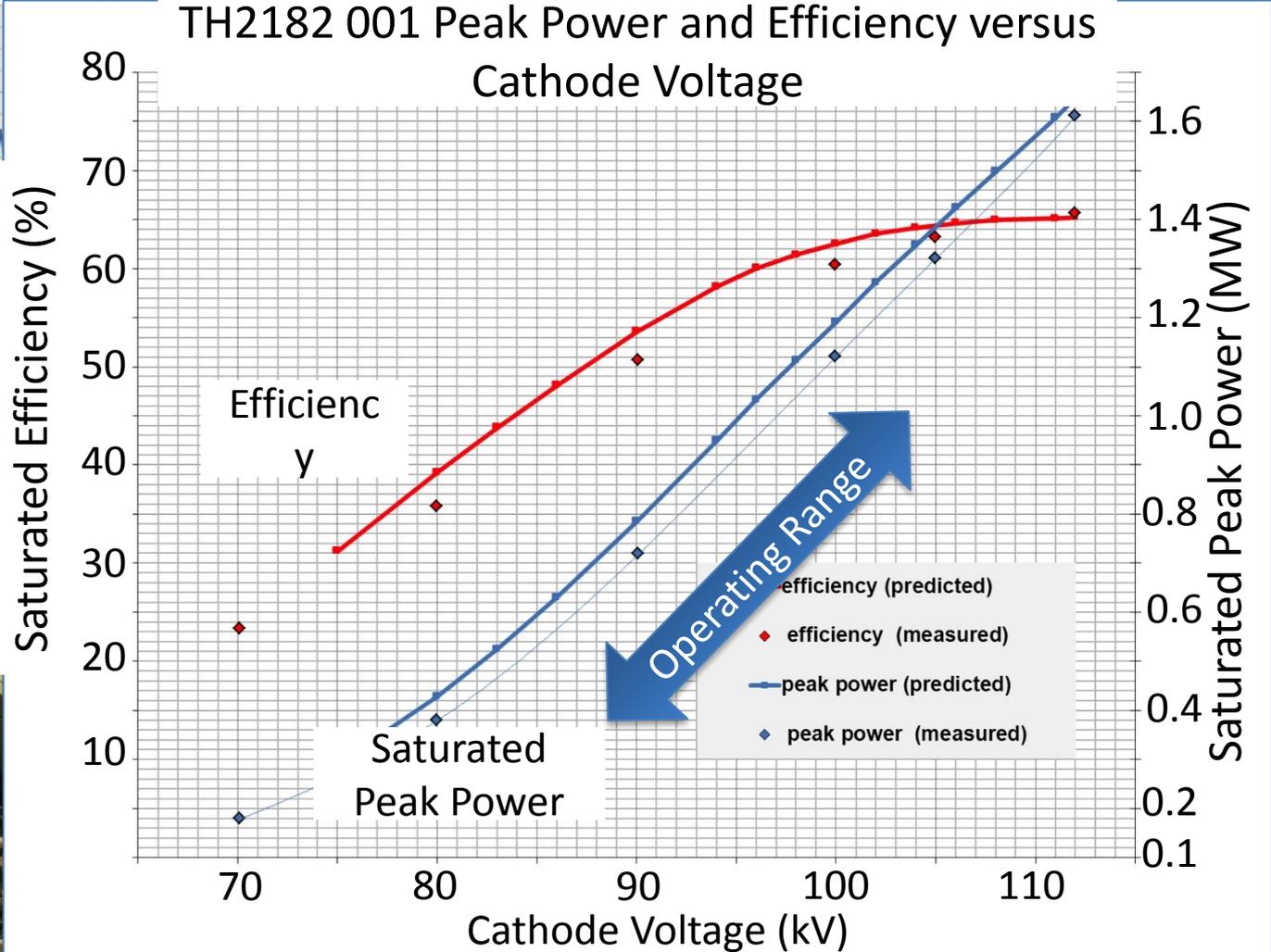
Racks moved to allow the cables to follow the route of the waveguide

# 704 MHz Klystron (Thales) factory tests

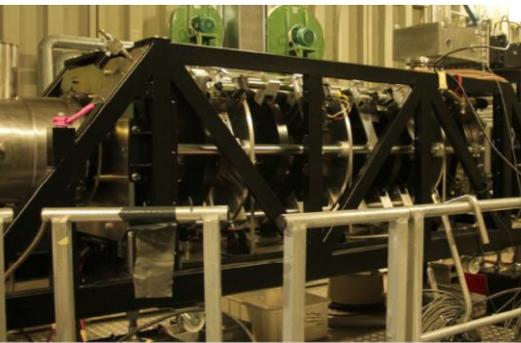
curve 1 TH2182 001 power transfer curve @ 50Hz 1.7ms



## TH2182 001 Peak Power and Efficiency versus Cathode Voltage

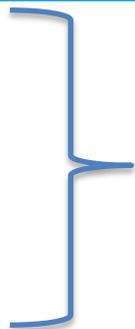


Courtesy of Thales and CERN



# An RF Source for a Proton Linac

- NC cavities with electrons
  - Operation at full power
  - 'Easy' to manufacture
  - Long cavity strings, no Lorentz detuning
  - Flat power profile – large source feeding many cavities



Very high power klystron  
is a good match

- Compared to copper cavities, superconducting cavities offer:

- over three times the gradient
- over 10 times the aperture
- with virtually no power dissipated in the cavities
  - SC cavities are difficult to manufacture
  - Cell structure designed for one beam velocity
  - Power profile shaped by transit time effects
  - Strong individual Lorentz detuning
    - Short Cavity strings – lower power
    - One amplifier per cavity

SRF supported by  
R&D and investment

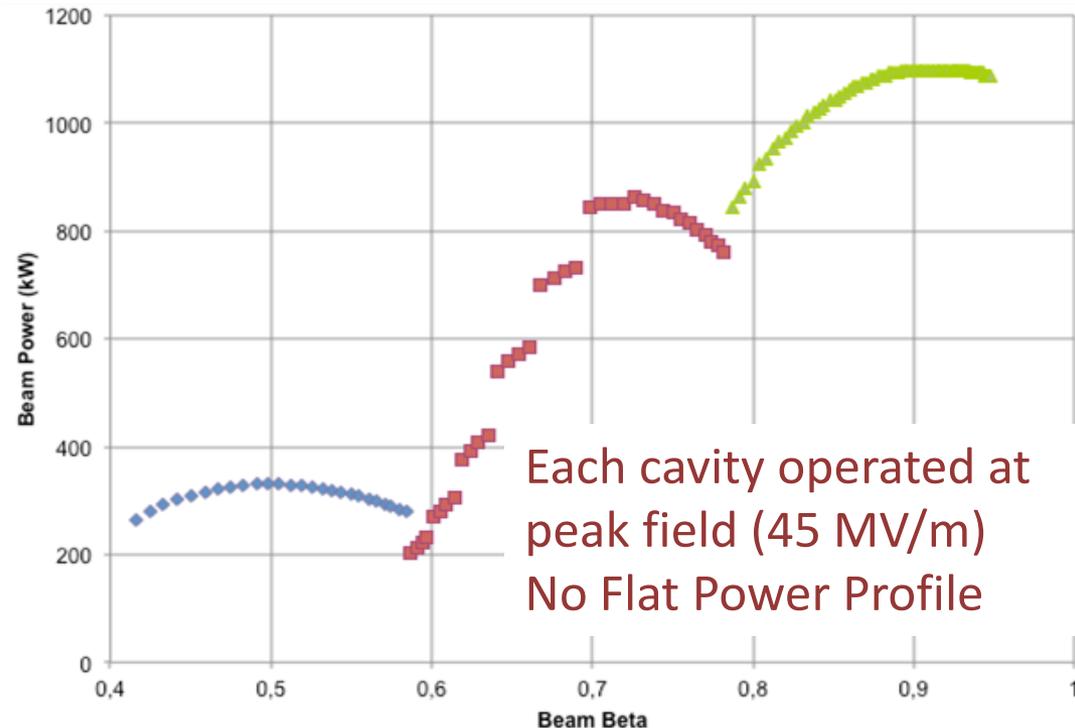
# An RF Source for a Proton Linac

Investment in SRF has not been matched with investment in high efficiency RF sources

In a klystron operation below saturation is inefficient and reduces 'actual' efficiency

Power-to-beam efficiency  $\leq 43\%$

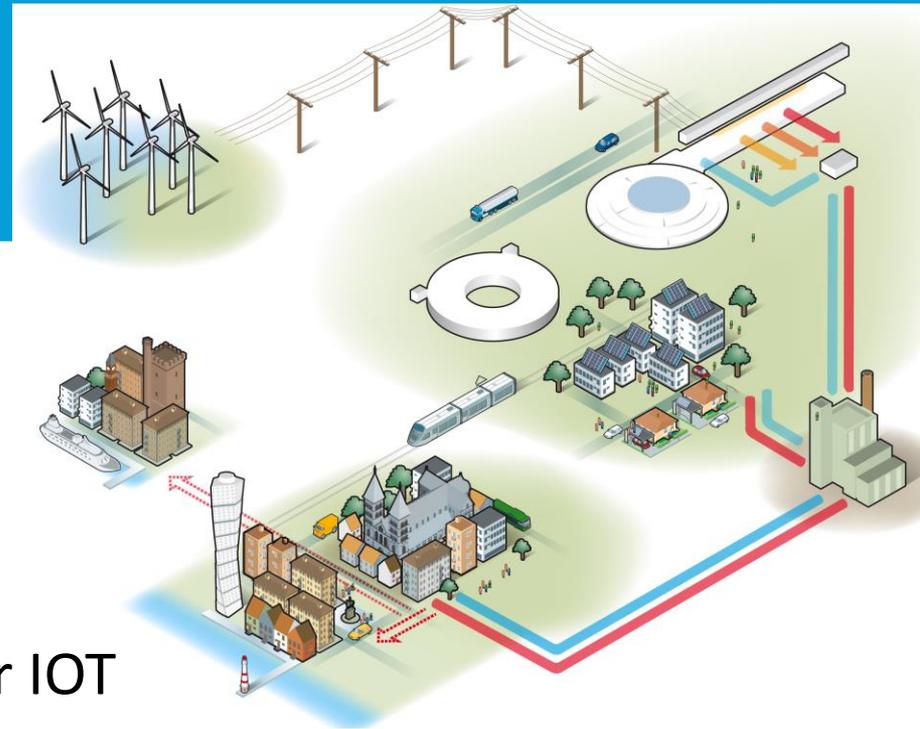
## Power Profile



# Where next?

## The ESS Requirement

Carbon Neutral  
Innovative  
Green



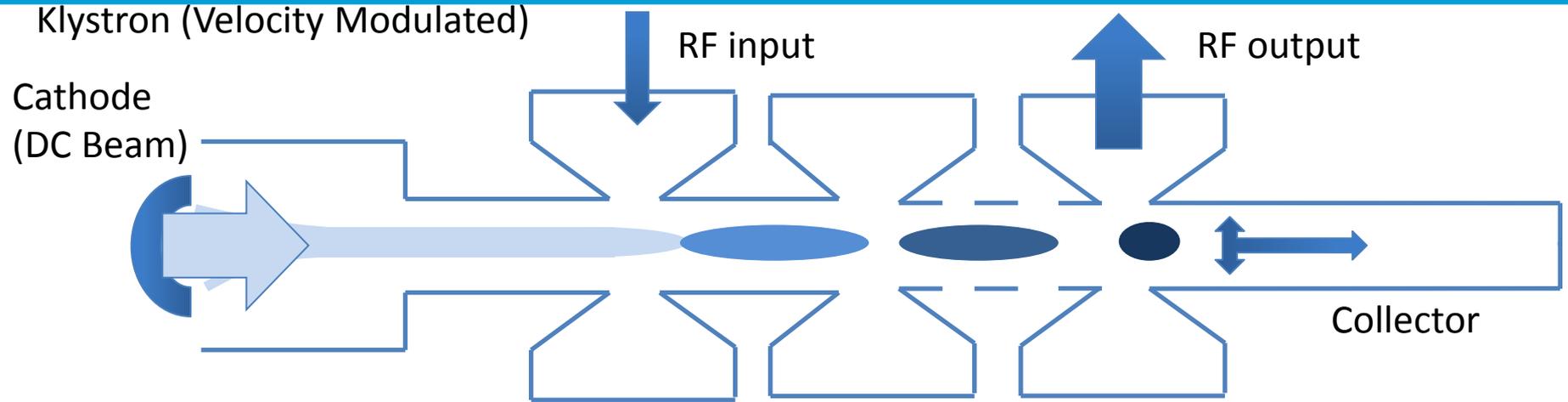
## Opportunity to develop Super Power IOT

| 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

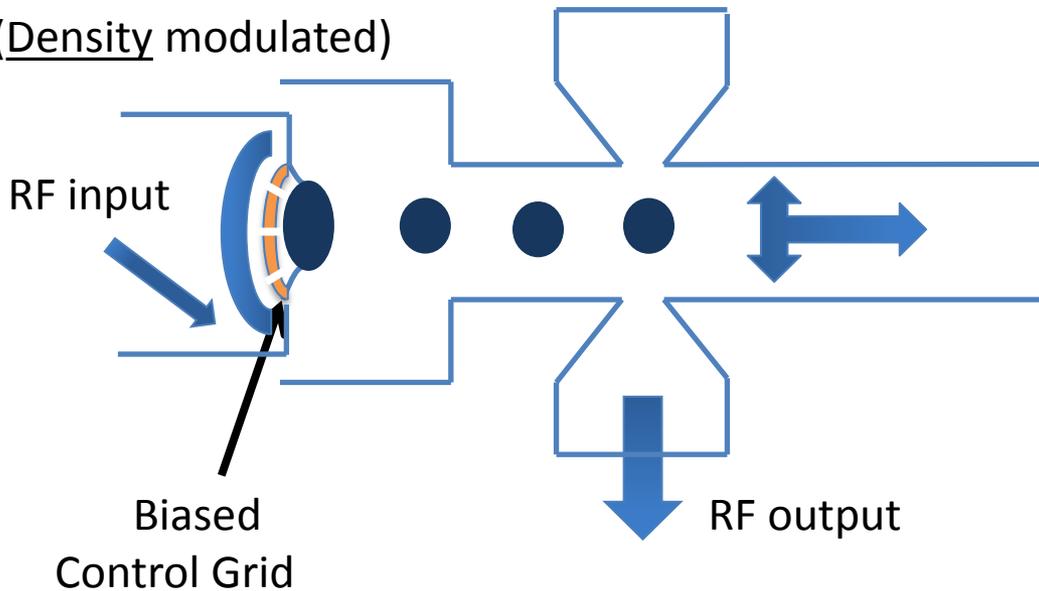
# Klystron and IOT Principles

Klystron (Velocity Modulated)



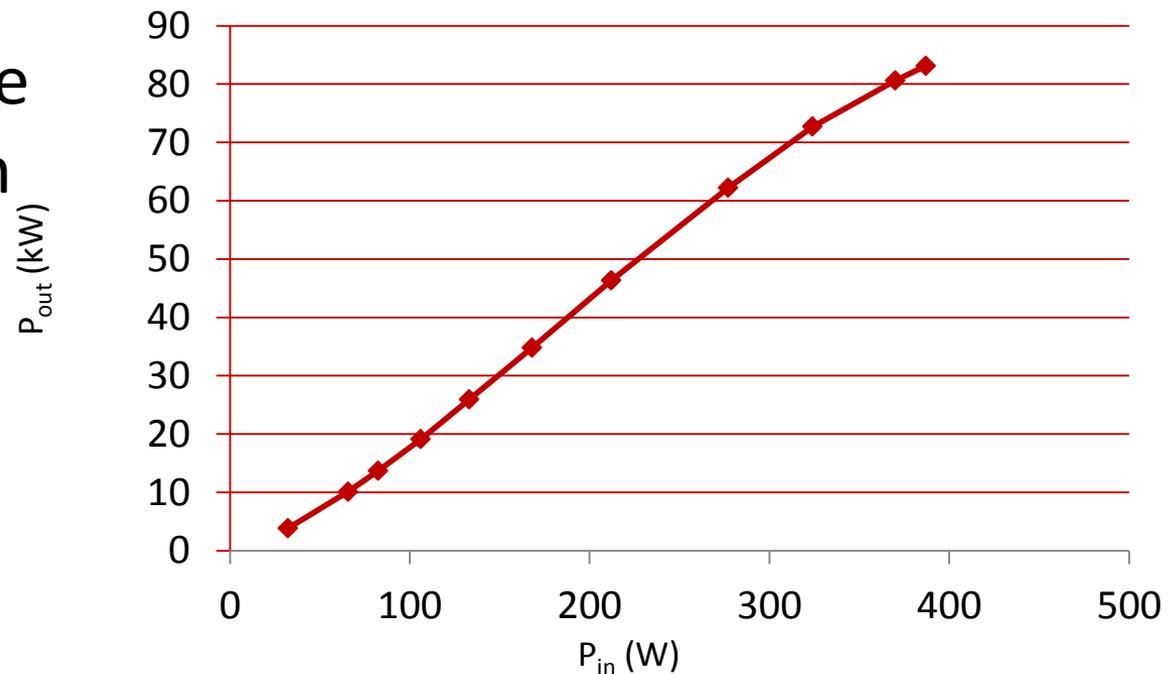
IOT

(Density modulated)



Reduced velocity spread  
Higher efficiency  
No pulsed high voltage  
No classical saturation

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



Courtesy of e2v

#### Tube History:

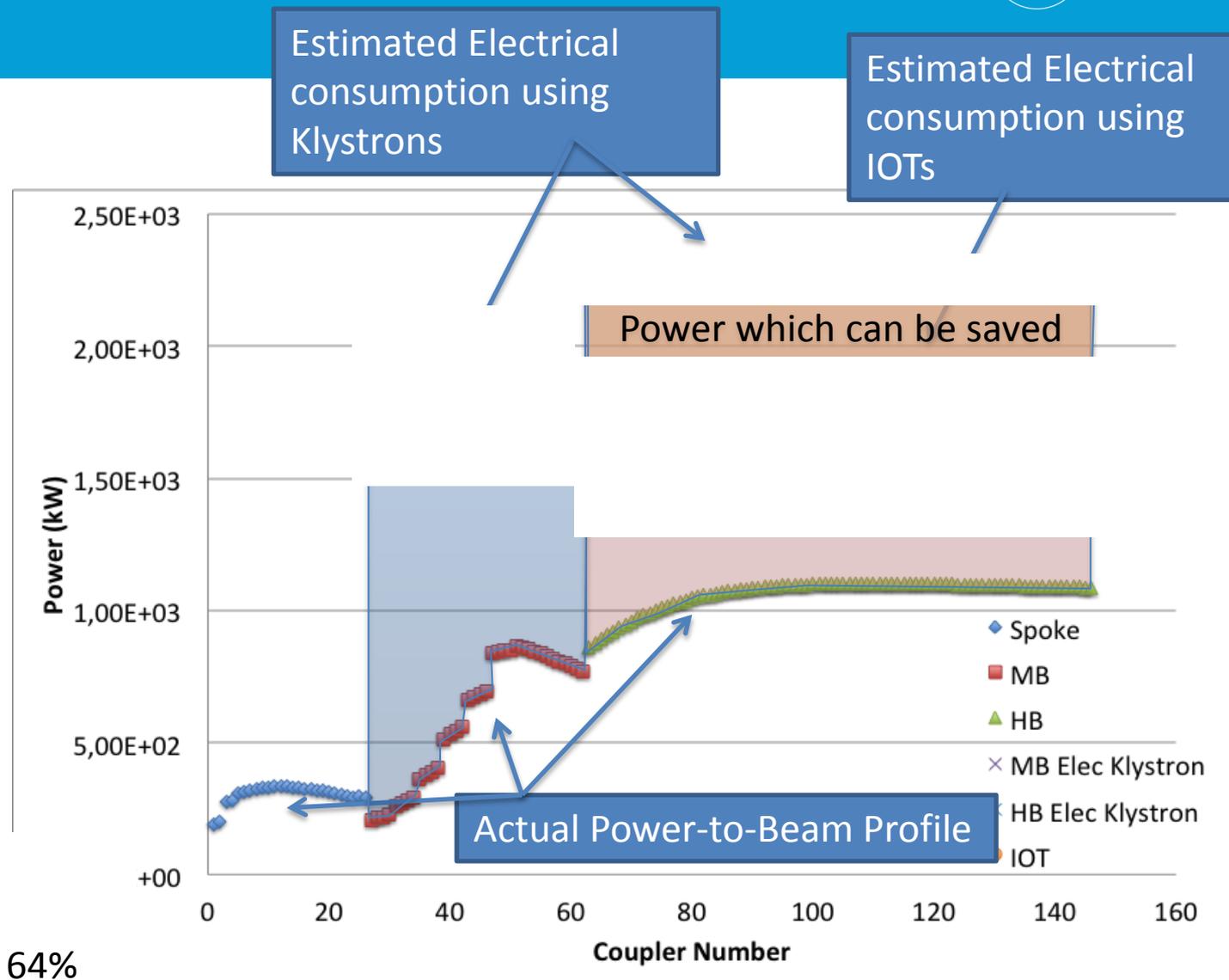
Invented in 1938 by Andrew V. Haeff as a source for radar.

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

Difficult to manufacture.

# An RF Source for a Proton Linac

Each marker is  
an RF Source



Assume 25% overhead  
Modulator  $\eta = 93\%$   
Klystron saturation  $\eta = 64\%$   
IOT  $\eta = 65\%$

| Parameter            |                   | Comment                               |
|----------------------|-------------------|---------------------------------------|
| <b>Frequency</b>     | <b>704.42 MHz</b> | <b>Bandwidth &gt; +/- 0.5 MHz</b>     |
| <b>Maximum Power</b> | <b>1.2 MW</b>     | <b>Average power during the pulse</b> |
| 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**

# A 3<sup>rd</sup> Generation Light Source Storage Ring

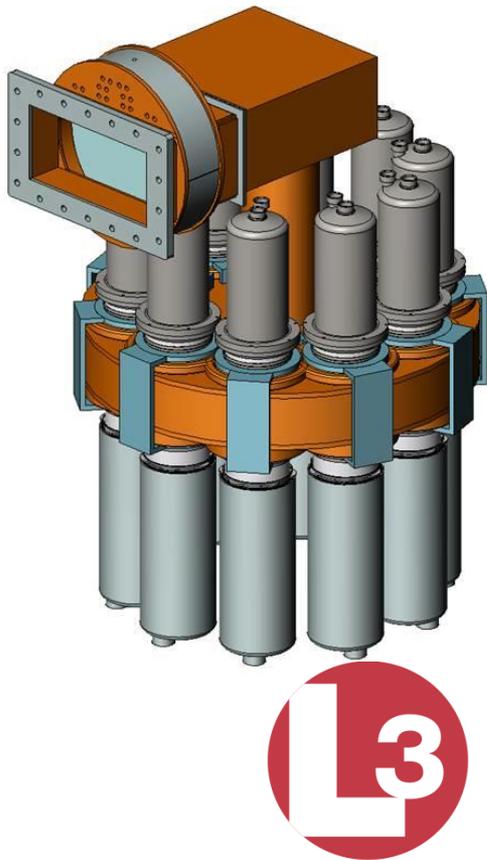


Three 500 MHz 300 kW amplifier for SR  
- 4 x 80 kW IOT combined  
One 80 kW for the Booster

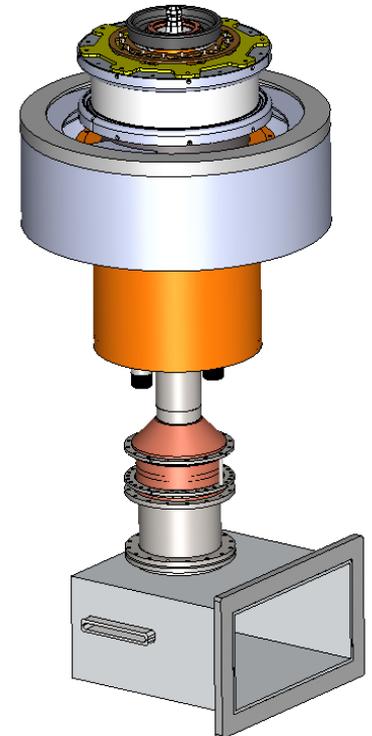


Other examples of IOTs exist  
throughout Europe  
... but not at MW power levels

# 1.2 MW Multi-Beam IOT



- ❖ ESS launched tender for IOT prototypes
- ❖ Tender replies received and contracts about to be signed for two IOTs
- ❖ 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



Pre-tender  
CPI Cartoon

# Summary of Key Parameters for the ESS High Power Devices



|                                    | Klystron<br>352 MHz | Tetrode*<br>352 MHz | Klystron<br>704 MHz | IOT<br>704 MHz                 |
|------------------------------------|---------------------|---------------------|---------------------|--------------------------------|
| Peak output power (MW)             | 2.8                 | 400                 | 1.5                 | <b>1.2</b>                     |
| Frequency (MHz)                    | 352.21              | 352.21              | 704.42              | <b>704.42</b>                  |
| Gun                                | Diode gun           | Filament            | Diode gun           | <b>Gridded Gun</b>             |
| Pulse length (ms)                  | 4                   | 3.5                 | 4                   | <b>3.5</b>                     |
| Rep. rate (Hz)                     | Up to 14            | Up to 14            | Up to 14            | <b>Up to 14</b>                |
| Maximum Beam Voltage (kV)          | 115                 | 18                  | 115                 | <b>50</b>                      |
| Efficiency at nominal output power | $\geq 55\%$         | $> 65\%$            | $> 60\%$            | <b><math>&gt; 65\%</math></b>  |
| - 1dB Bandwidth (MHz)              | $\geq +/- 1$        | $\geq +/- 3$        | $\geq +/- 1$        | <b><math>\geq +/- 1</math></b> |
| Gain (dB)                          | $\geq 40$           | $>15$               | $\geq 40$           | <b><math>\geq 20</math></b>    |

# Acknowledgements



Thank you to RF Group at ESS for support and content

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