# ESS RF Systems

Rutambhara Yogi & RF group

Outline of talk:

- Introduction to ESS
- RF Systems
- High Power Amplifiers

  (IOT, Klystron, Tetrode, Solid State)
- RF Distribution

# European Spallation Source (ESS)


Ground breaking: Jan Björklund (Swedish Research minister), Sofie Carsten Nielsen (Danish Research minister:2 September 2014

Most powerful neutron source in the world by end of the decade

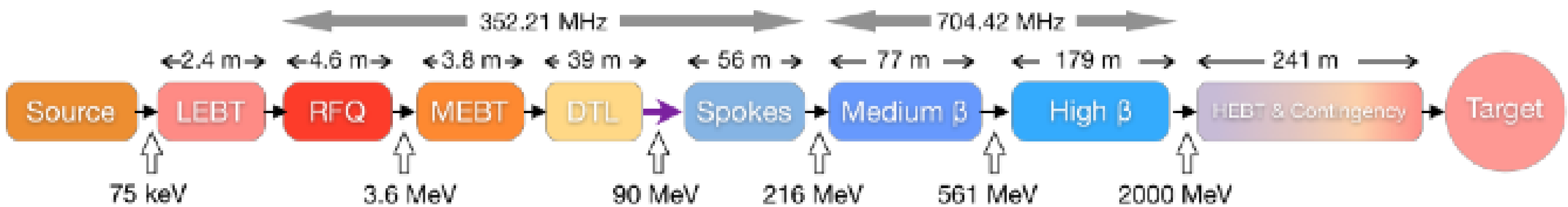
>22 European countries as partners

Being constructed in Lund, Southern Sweden

# Accelerator buildings

# ESS Linac

Optimus+_2013_10_31




Warm linac

Superconducting linac

≈ 2 %

≈ 98 %

Long pulsed superconducting linac

Proton beam current = 62.5 mA

Average proton beam power to the target = 5MW — 5 times more than SNS

Peak beam power to target = 125 MW — 7 times more than SNS

Beam pulse width = 2.86 ms

Pulse repetition frequency = 14 Hz

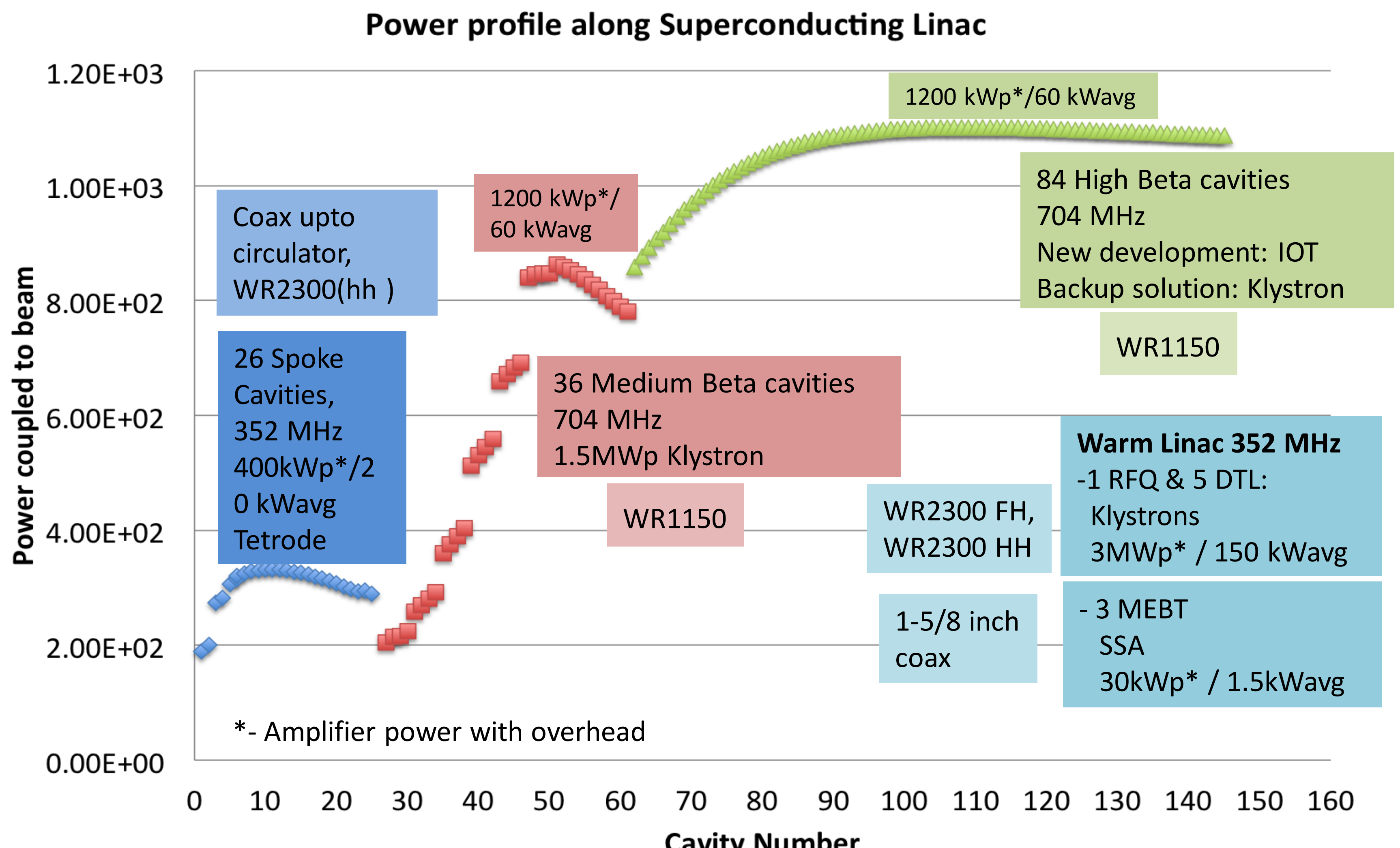
**Aim:**

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

# RF Group Responsible for:

- Providing RF power to proton beam – Amplifiers, Pre-amplifiers, RF Distribution, Modulators.
- Arc detection on RF systems and cavities
- Slow and fast Interlocks on RF systems & Fast Interlocks on cavities
- Quench detection on cavities
- Start up procedure of the cavities
- LLRF
- Master Oscillator
- Phase reference line

# RF Power profile



# RF Source requirements for MB/HB

Courtesy: Morten Jensen

- Medium Beta
  - 36 transmitters
  - Based on 1.5 MW klystron, 704 MHz
  - One transmitter chain per cavity, one modulator per 4 klystrons
  - Three prototypes (Toshiba, Thales, CPI) developed by ESS
- High Beta
  - 84 transmitters
  - Based on 1.2 MW IOT, 704 MHz
  - Medium Beta klystrons as backup
  - Otherwise similar to medium beta
  - Two prototypes (L3, Thales-CPI consortium) developed by ESS

# Medium (and High) Beta amplifiers

**Medium Beta**
200 kW to 866 kW (plus 30%)
-> saturated power from klystrons up to 1.15 MW

## Klystron specifications

| **Nominal output power** | **1.5 MW** |
|---|---|
| **Frequency** | **704.42 MHz** |
| BW | ≥ +/- 1 MHz |
| Pulse width | 3.5 ms |
| Repetition rate | 14 Hz |
| Conversion Efficiency | >60% (at saturation) |
| VSWR | Up to 1.2 |
| Power Gain | ≥ 40 dB (may be increased) |
| Group Delay | ≤ 250 ns |
| Harmonic Spectral content | ≤ -30 dBc |
| Spurious Spectral content | ≤ -60 dBc |

**High Beta**
835 kW to 1.1 MW (plus 30%)
1.2 MW **MBIOTs** (or klystrons as backup)

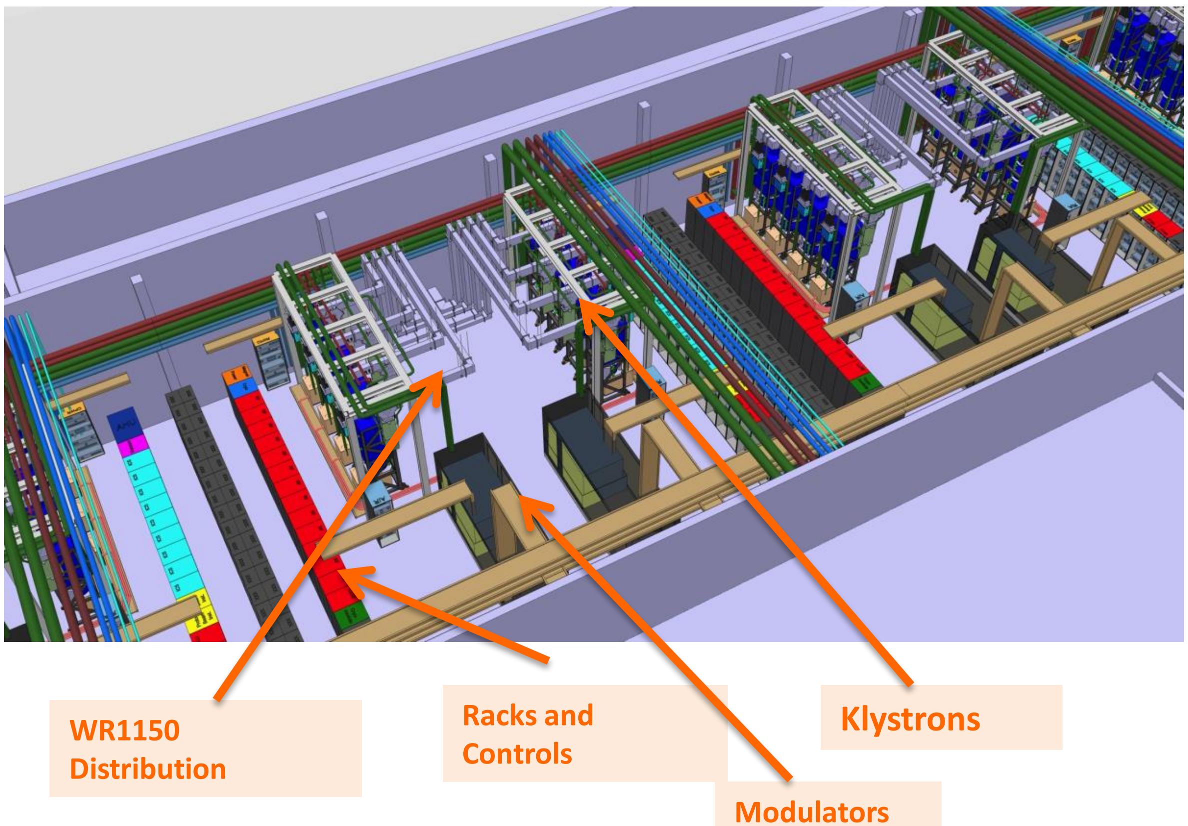
## MBIOT specifications

| Peak output power | > 1.2 MW |
|---|---|
| Frequency | 704.42 MHz |
| BW | ≥ +/- 1 MHz |
| Pulse width | 3.5 ms |
| Duty factor | Up to 5% |
| Conversion Efficiency | >65% (at point of operation) |
| Overall efficiency (including idle current) | >65% |
| Gain | > 20 dB |
| Beam Voltage | < 50 kV |
| Beam current | < 45 A rms |
| Tube life | ≥ 50 khrs |

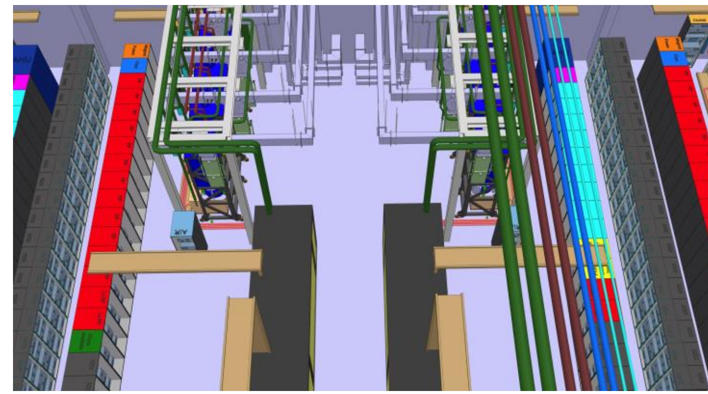
# Medium Beta klystrons

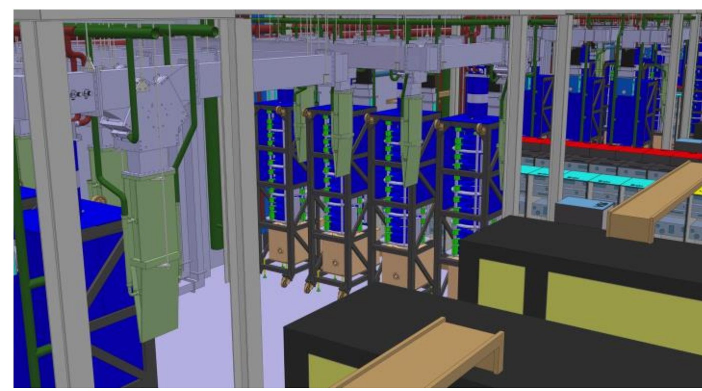
EUROPEAN
SPALLATION
SOURCE

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



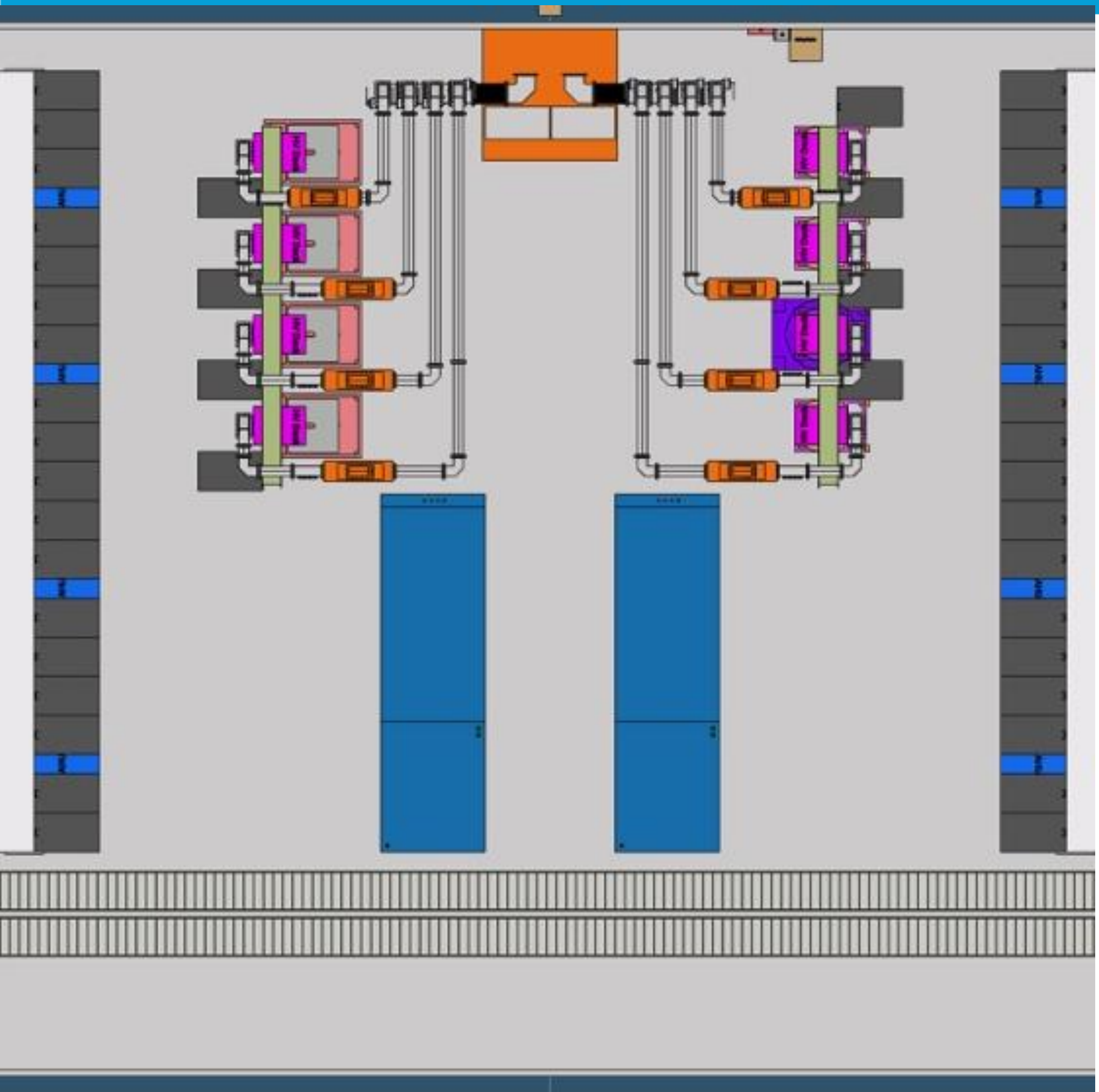

One 660 kVA modulator will power 4 klystrons





The klystrons will have vertical orientation in order to fit in the gallery

# MBIOT - 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)

# Medium Beta klystrons

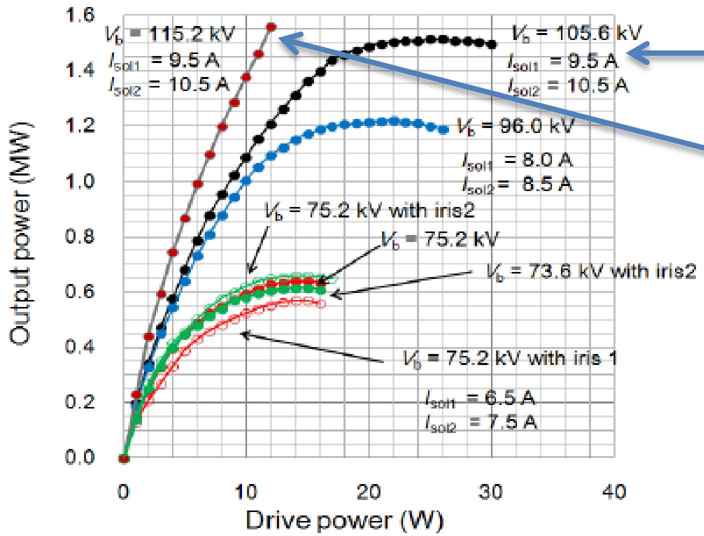
- Thales prototype contract placed January 2015
  - First pass – Arcing in window region
    - Factory Acceptance Test cancelled
    - Tube opened for inspection
    - Additional failure analysis and extra window design review held
  - New window brazed
    - Braze failed quality inspection
    - New parts ordered
    - Problem with vacuum
    - Factory Acceptance Test expected in Dec, delivery in Jan 2017

- Toshiba prototype contract placed February 2015
  - Delivered (March 2016)

- CPI prototype contract placed April 2015
  - Factory Acceptance 28 September (not observed)
  - Observed Factory Acceptance test week of 10 October 2016
  - Phase is not monotonous.
  - New FAT expected in November 2016

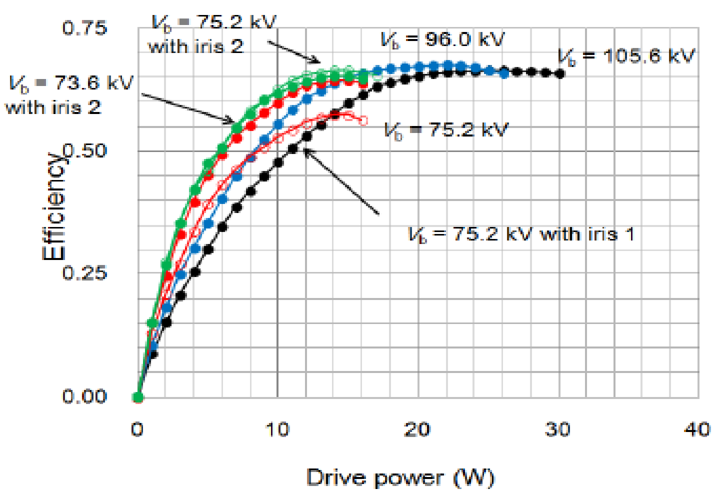
# Toshiba klystron E37504 prototype

Some results from the **Factory Acceptance Test** (February 2016):




1.5 MW

Performance at 115 kV



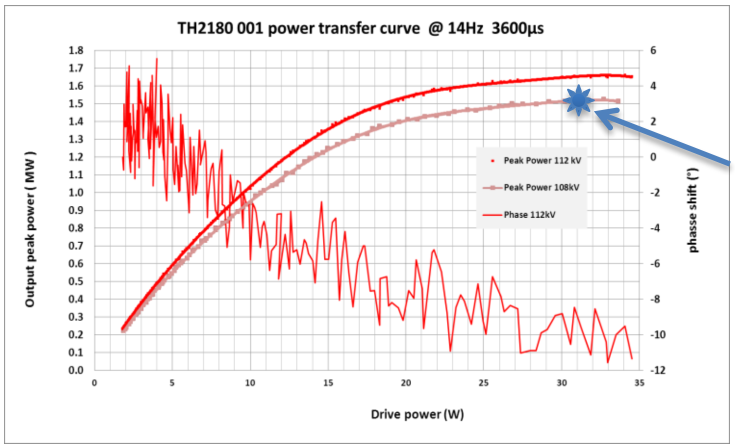

> 60% efficiency even at 600 kW

**Klystron accepted and delivered to Lund!**

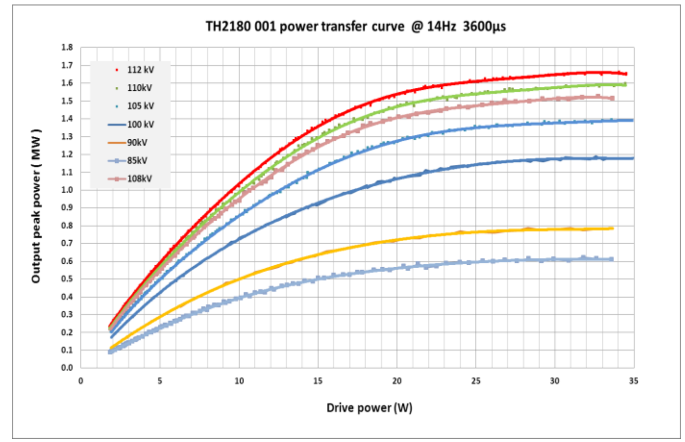
# Thales klystron prototype TH2180

**The tube has been tested at factory at full power for few days in May 2016.**

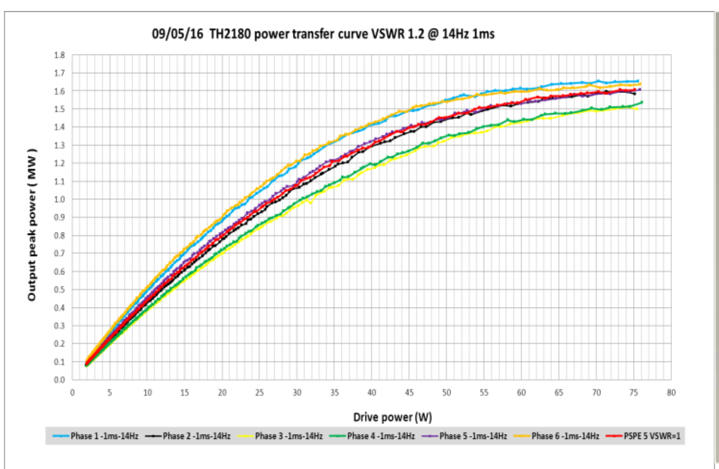
Saturated efficiency 66%.

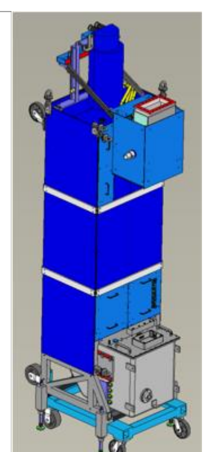


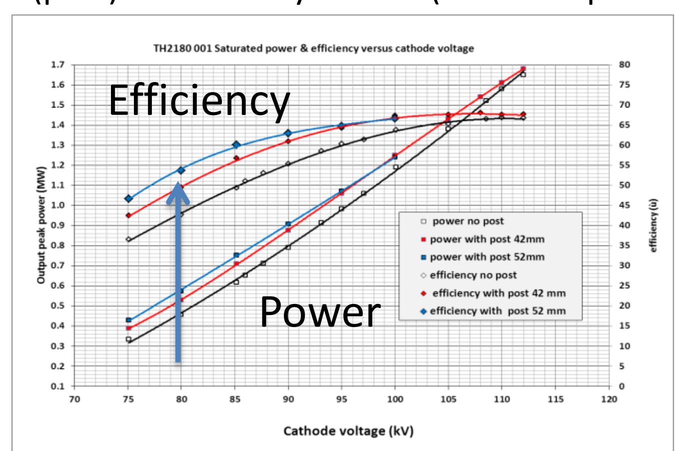

1.5 MW
at 108 kV




Operation at low beam voltage: efficiency can be increased by using a mismatch at the output (post). Preliminary results (can be improved):



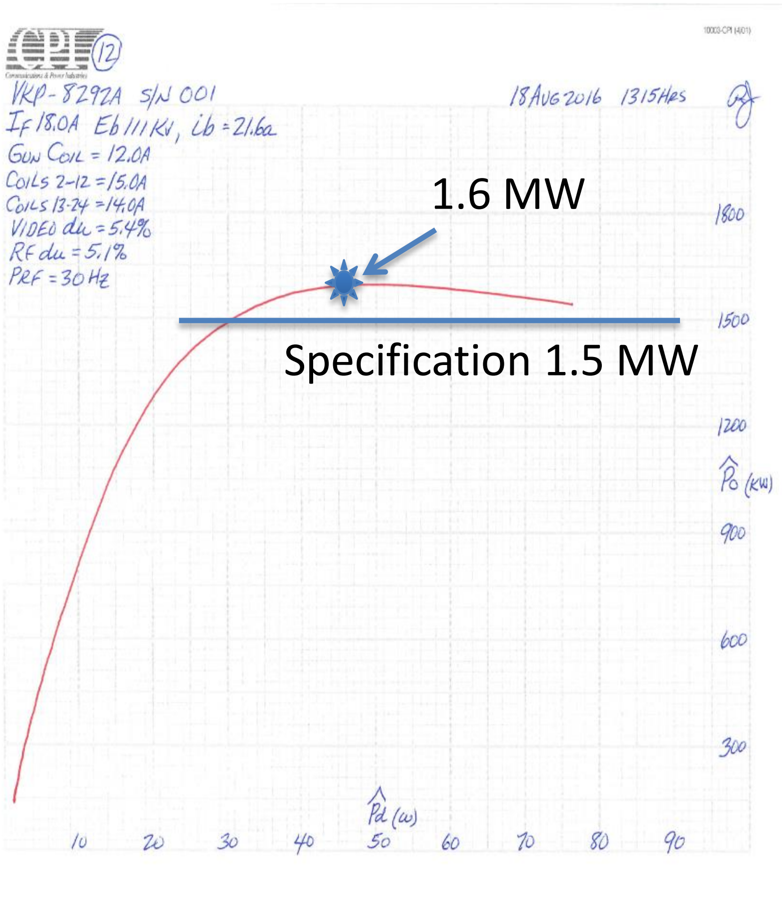





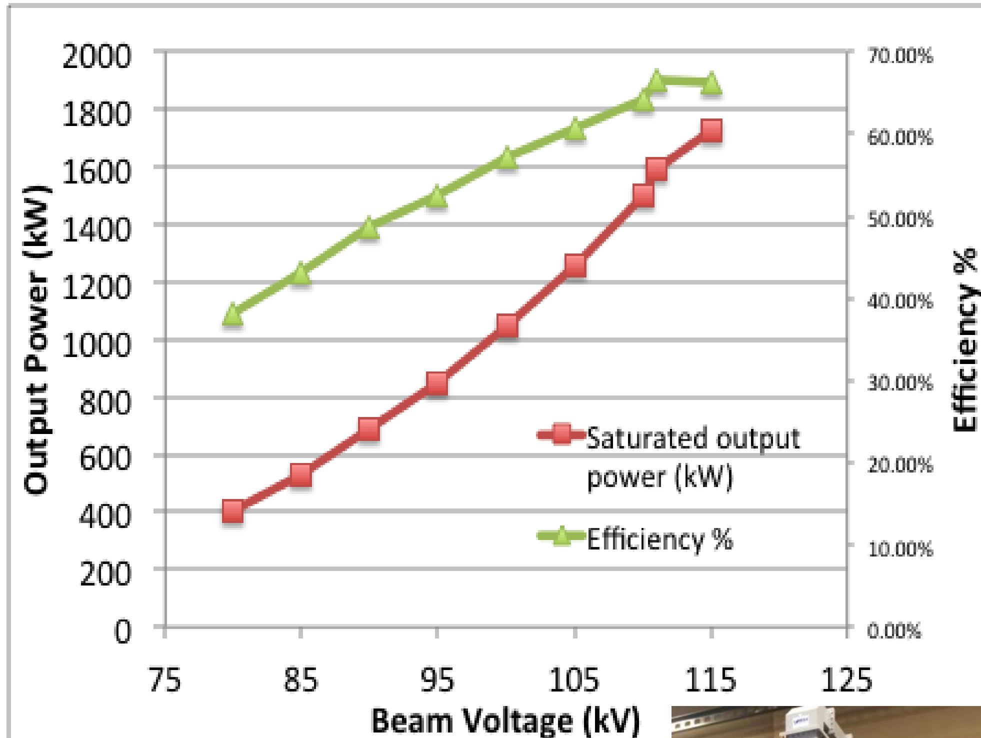

1.5 MW
65%

600 kW
55%
80 kV

# CPI results (Preliminary Factory Tests)



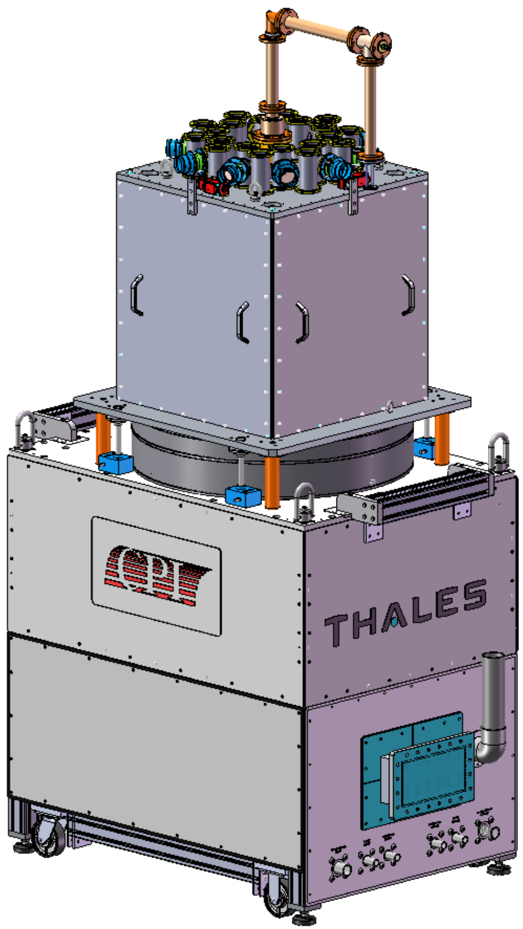

Transfer curve at nominal 111 kV




Output power and Efficiency vs Beam voltage

# Multi-Beam IOTs for ESS

EUROPEAN SPALLATION SOURCE




## 10 Beam Multi-Beam IOT
## 1.2 MW
## 704 MHz

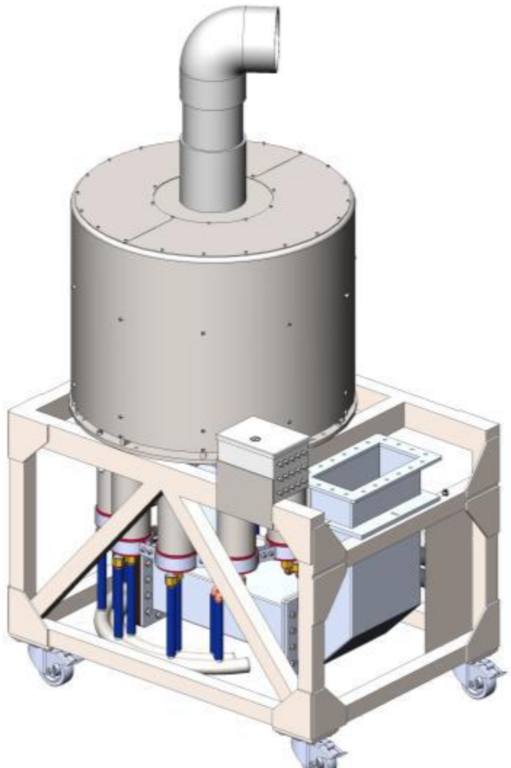
Two Contracts for **Technology Demonstrators**

- 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

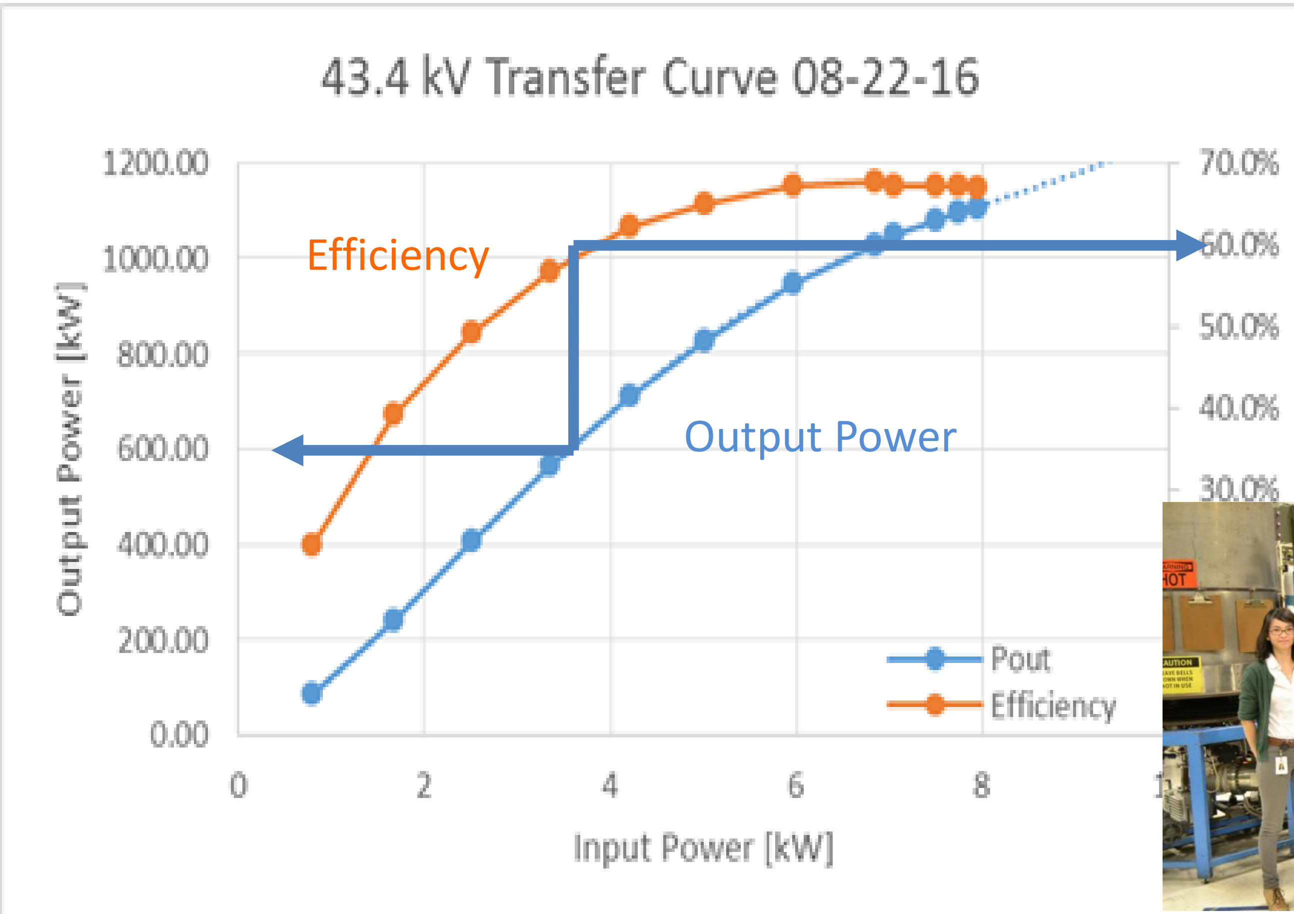
# Solid State Driver

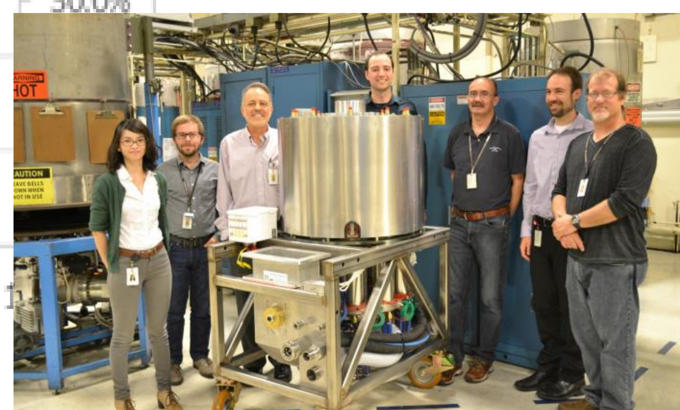
TOMCO 15 kW driver being used for Factory Testing at L3

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% |

# Preliminary Results

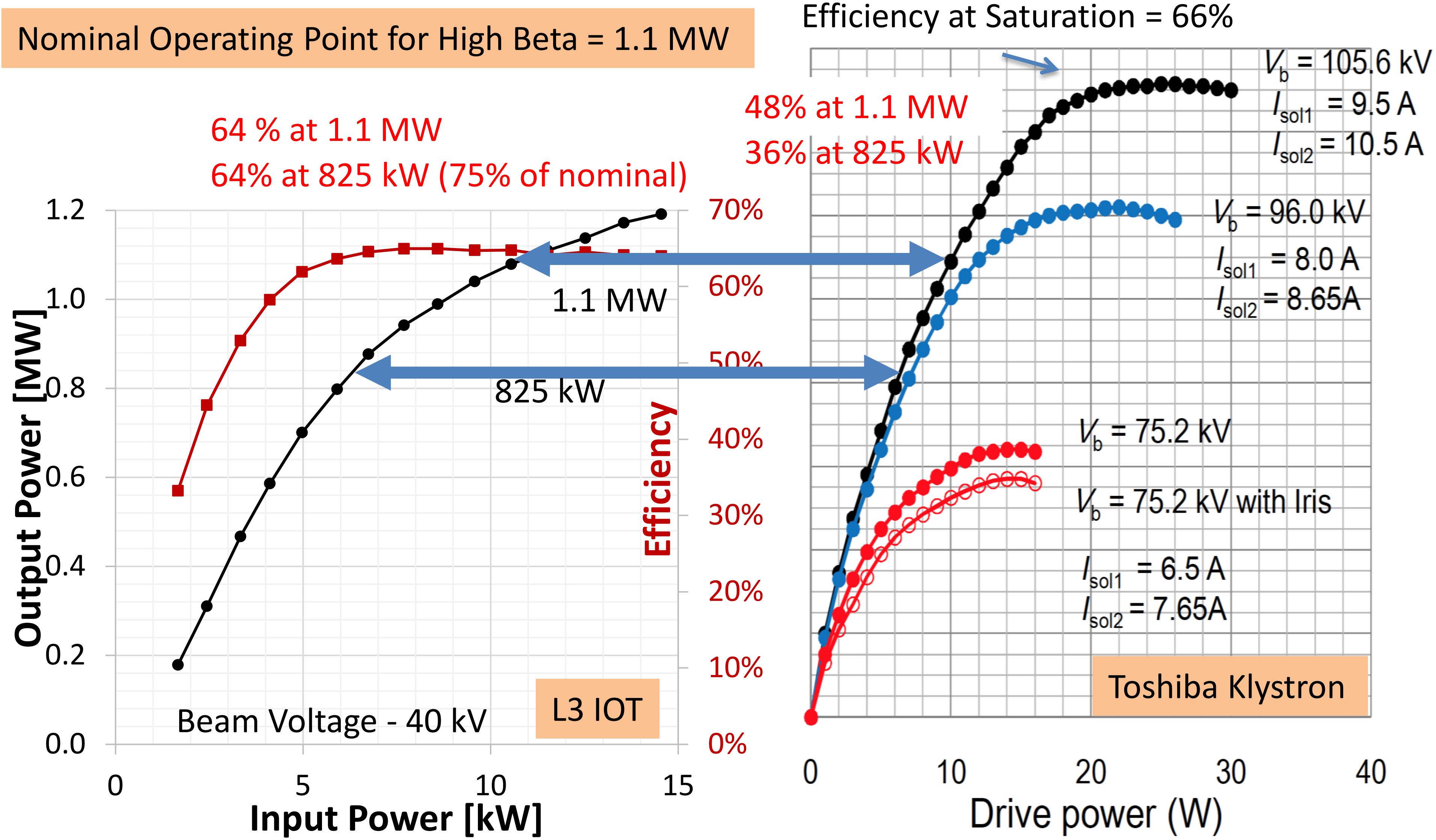


Efficiency ≥ 60% from 600 kW to 1.2 MW

(HV efficiency only)

# Comparison to Klystron

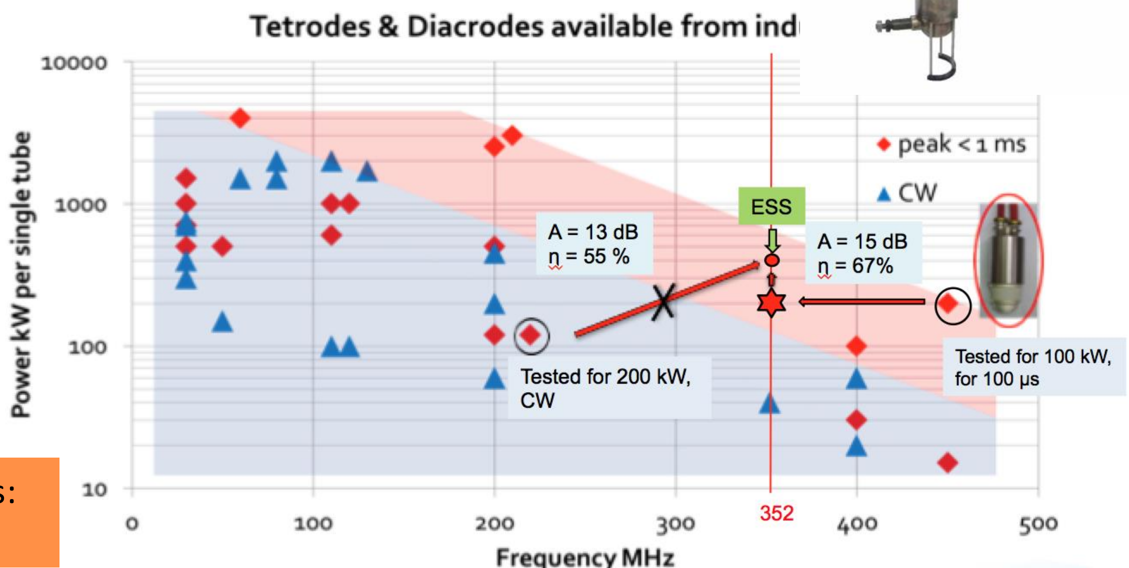


# Latest transfer curve


900 kW at 6% duty (200 micro s and 300 Hz)
1.2 MW at 2% duty (100 micro s and 200 Hz)

Droop limits the voltage to 44.8 kV but with 1.4 kV droop. Nominal should be 45 kV.

- Spoke:
  - 26 RF power stations
  - 400kW, 352 MHz
  - Output of two TH595 tubes combined
  - One High voltage power supply powers two tetrodes
  - Elettra Inkind

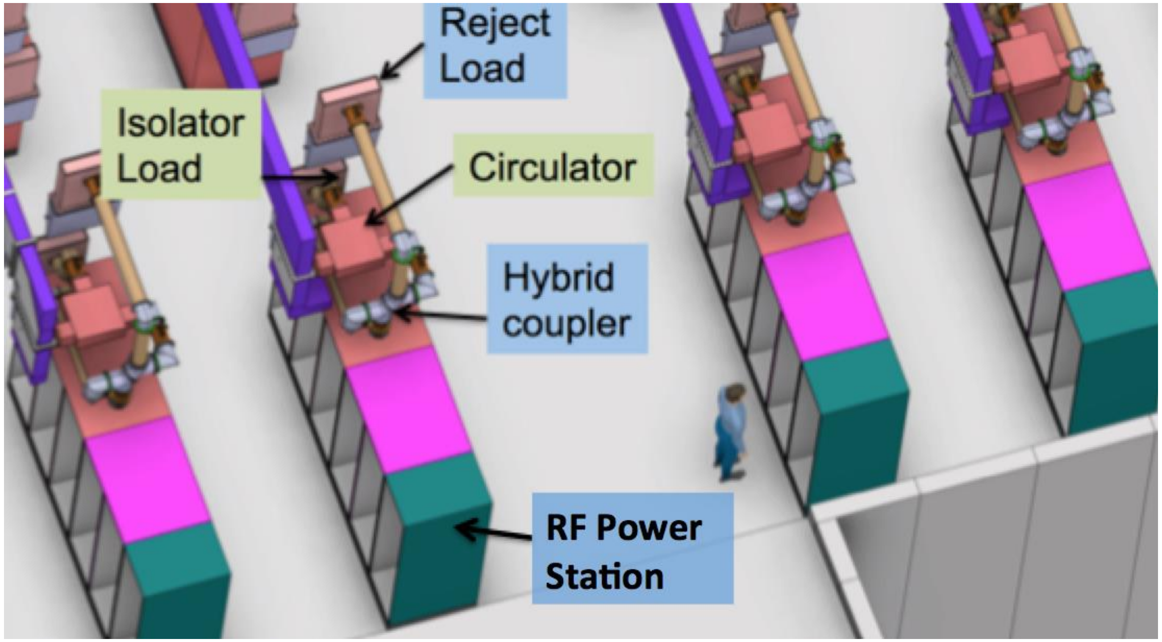




Courtesy: Data for Tetrode and Diacrodes:
Eric Montesinos (CERN)

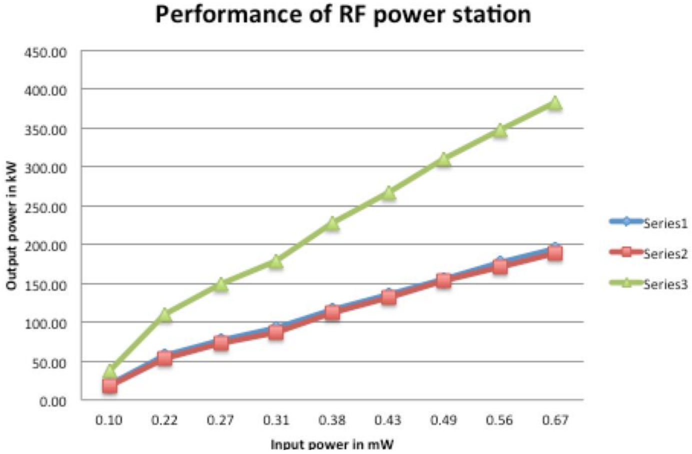
# RF Source requirements for SPK

3.25 cells of 16 Tetrodes

## Spoke Gallery




Preliminary Prototype tested at FREIA

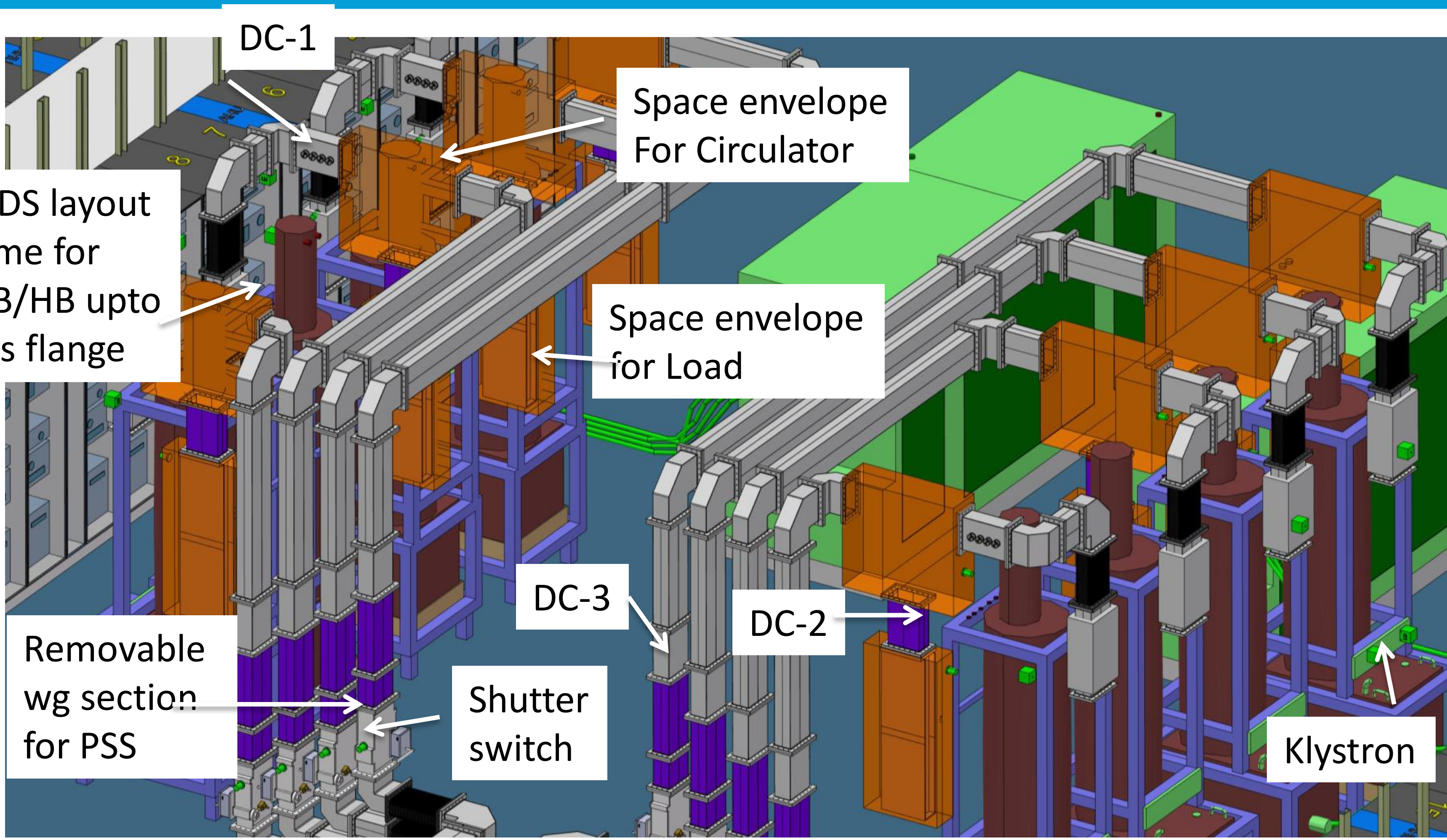



Courtesy: Magnus Jobs at FREIA

# High Power RFDS

- All high power RFDS – Inkind
- For Cold linac – Inkind by UK (STFC & HU)
  - Responsibility for design: ESS
  - Procurement and Delivery at site: UK
  - Design and delivary of support structure: UK
- For Warm linac – Inkind by ESS-Bilbao
  - Design, procurement, delivery - ESS-Bilbao
- Installation: ESS with polish inkind
- Testing and commissioning: Involvement of UK, ESS-Bilbao, Responsibility of ESS

# Concept of High Power RFDS layout



# High Power RF Distribution

## Approximate Numbers for Cold Linac

| Component | Spoke | Elliptical |
|---|---|---|
| Waveguide | 550m | 2725m |
| H bends | 130 | 600 |
| E bends | 78 | 600 |
| Bellows | 97 | 480 |
| DC | 78 | 360 |
| Arc detectors | 104 | 480 |
| Circulators, loads & switches | 26 | 120 |
| Coax elbows | 52 | |

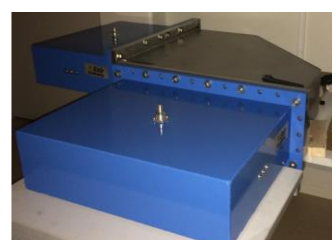
# Flange and waveguide design

Waveguide extends through the flanges

Fabrication becomes extremely easy and avoids discontinuities

Costs by metal manufacturers expected to be 20-30% cheaper than RF companies ~ MEUR


Received prototypes from two companies.



Waveguides by EXIR are installed in FREIA

# Schedule - RFDS for Cold Linac

1 : Waveguides and elbows (tender documentation being prepared)

2: Standard components (Tender evaluation, standstill period)

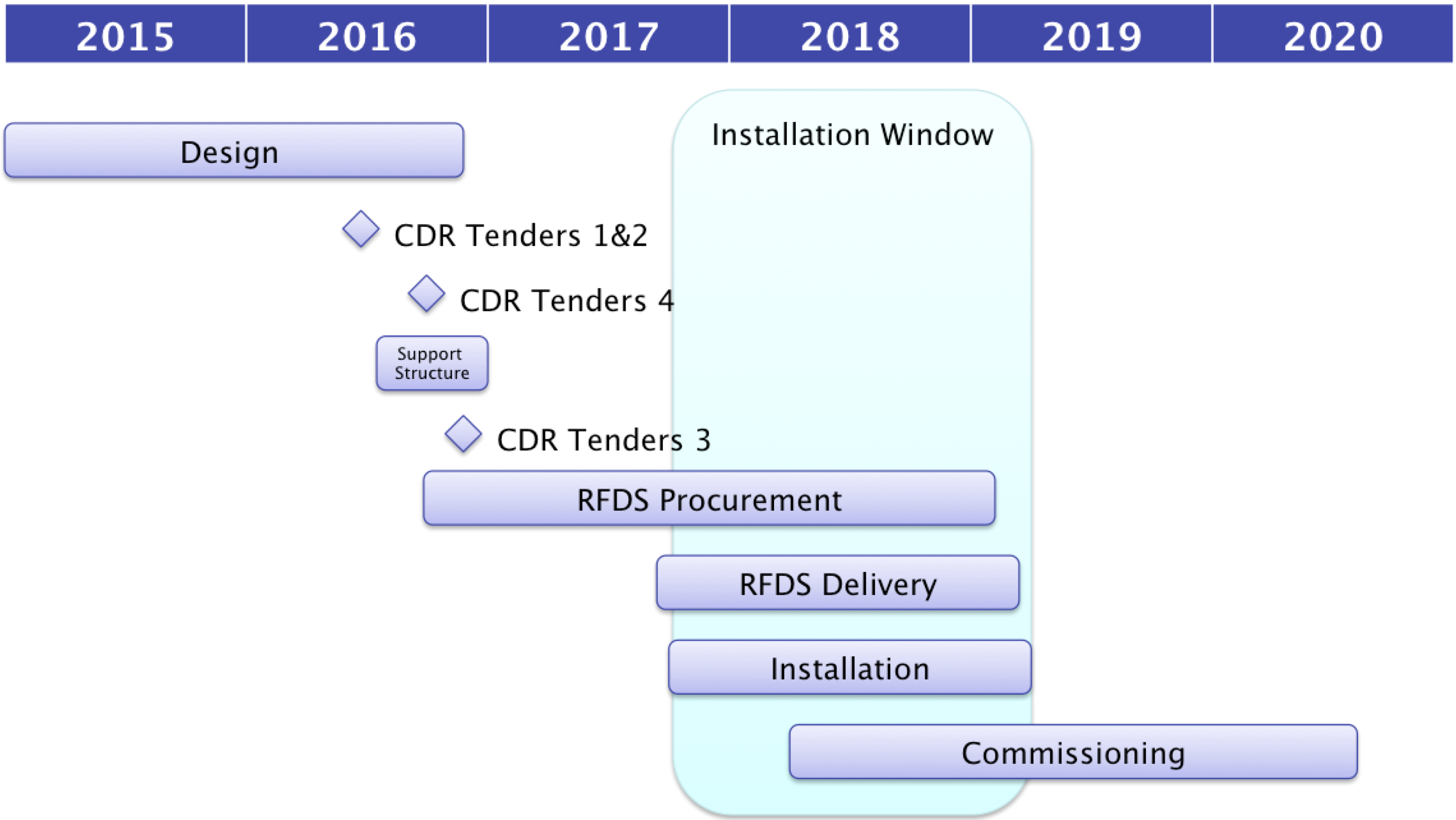
3: Support structure (Design in progress, prototype for test stub installation)*

4: Loads and Circulators (tender ready. Will be uploaded in this week)

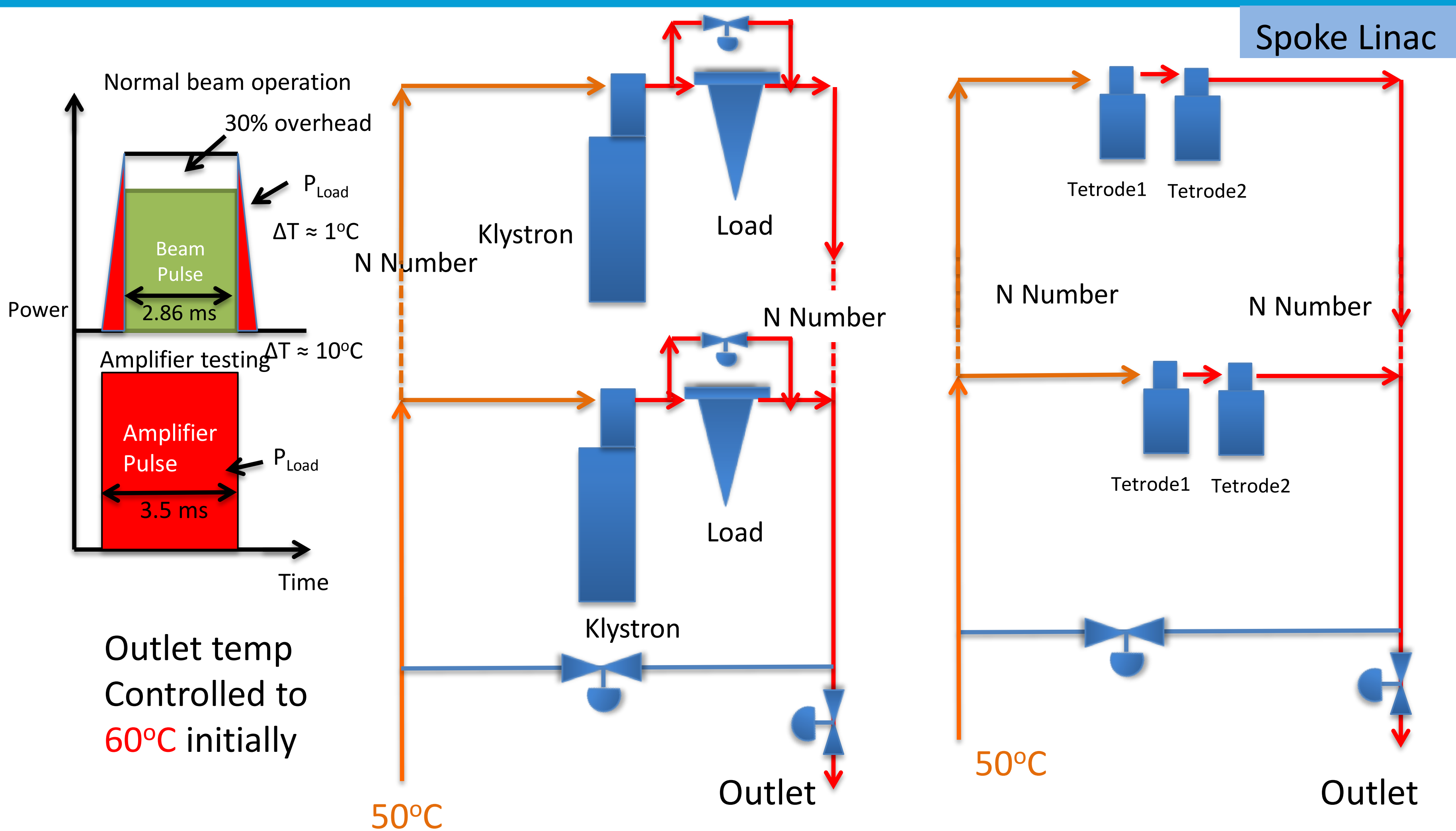
5: Arc detectors (Decision to be taken in ESS group in next week)

6: Swiches, Windows, Connections to Klystron,
Connections to SPK RF power station etc

# Schedule


2015
2016
2017
2018
2019
2020
Installation Window
Design
CDR Tenders 1&2
CDR Tenders 4
Support Structure
CDR Tenders 3
RFDS Procurement
RFDS Delivery
Installation
Commissioning

# HB / MB Linac: New development of loads

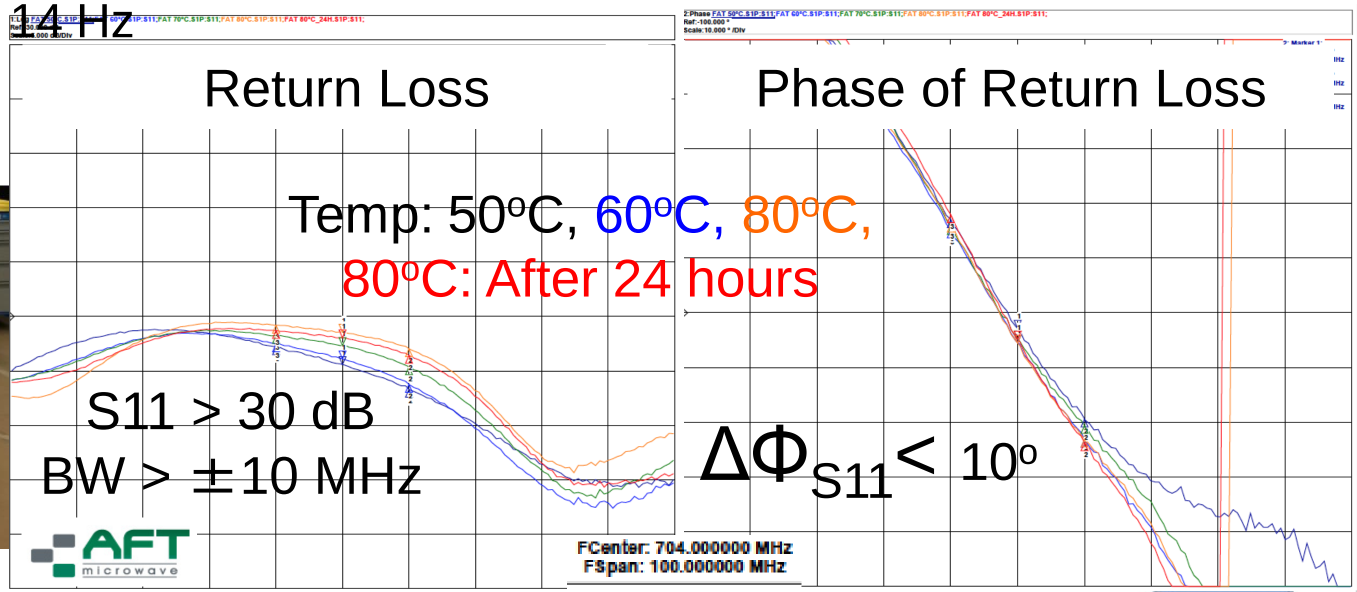



Outlet temp
Controlled to
60°C initially

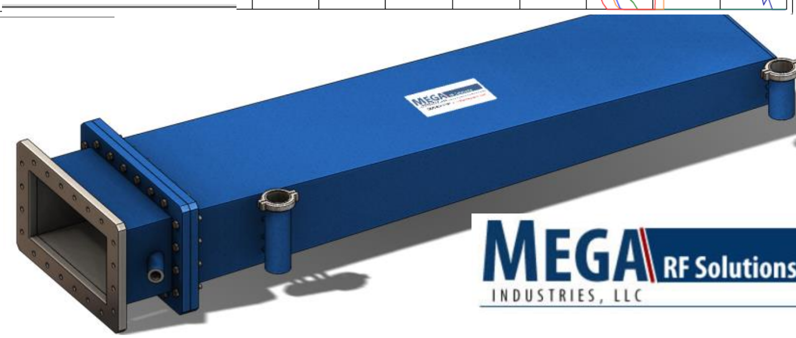
# New Load development for ESS
# Hot water cooled loads

Frequency = 704 MHz
Power ≥ 1500 kWp
Pulse width = 3.5 ms
Pulse repetition rate = 14 Hz

Inlet water temp ≥ 50º C,
Outlet water temp ≤ 80º C




Prototype by Thales will be delivered soon.



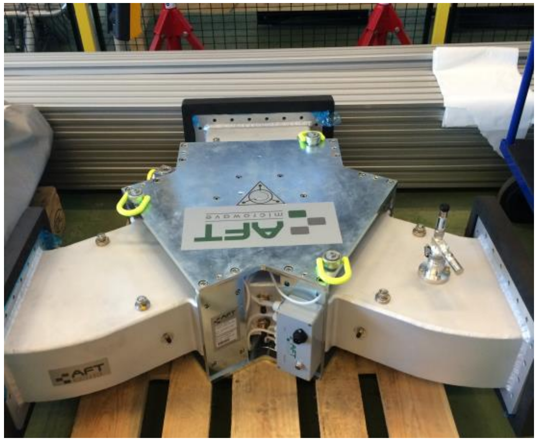
MB/HB prototype circulators:

AFT: Delivered at ESS- Similar to that delivered to CERN.

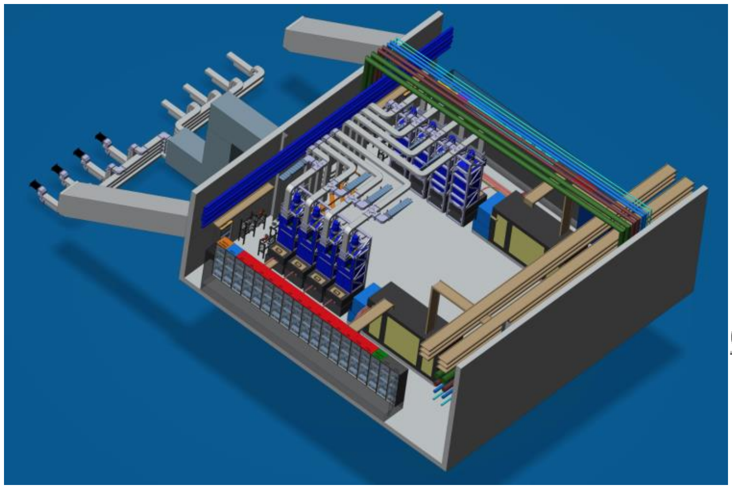
Change – configuration is T: to reduce two elbows

FMT: Passed FAT, Will be delivered at ESS very soon

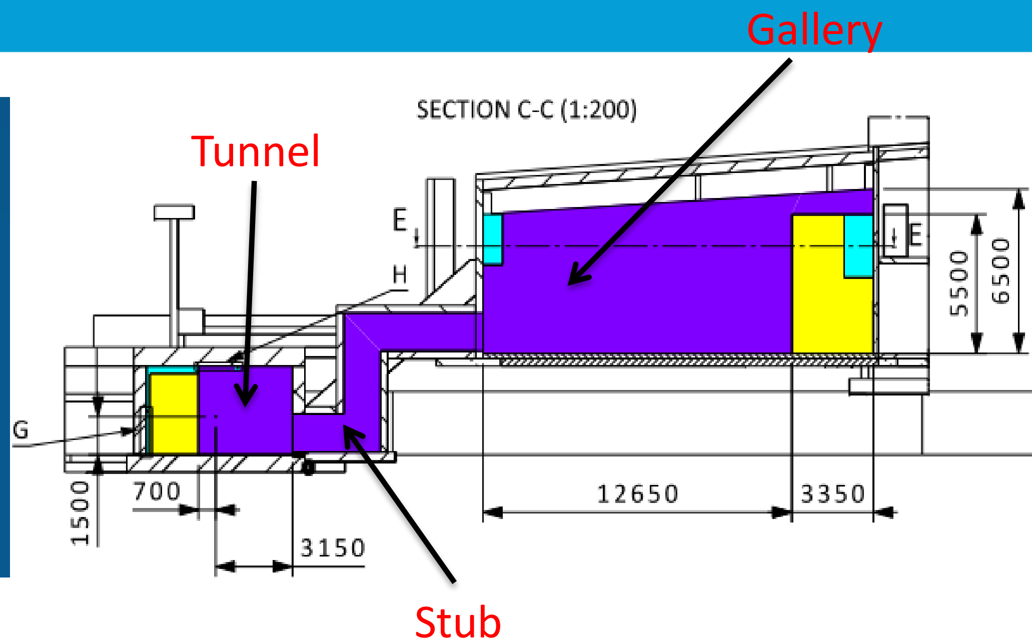
MEGA: FAT will be in next month



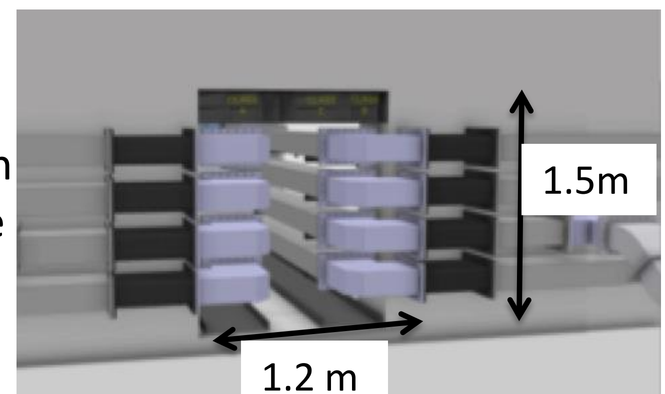
# Stub Mockup for High Beta Linac



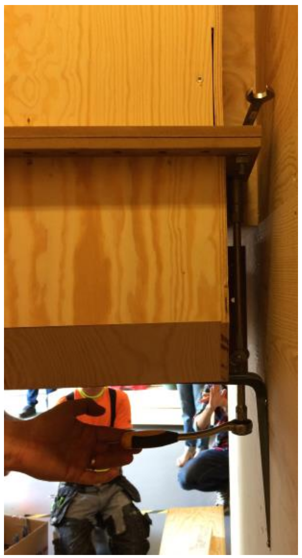
Earlier building layout




- Length optimization of Waveguides : to have minimum flange joints in the stub
- Layout optimization (minimum distance between flange and stub wall), to have maximum possible space for cables.
- Extremely important for building layout. So Mockup was performed

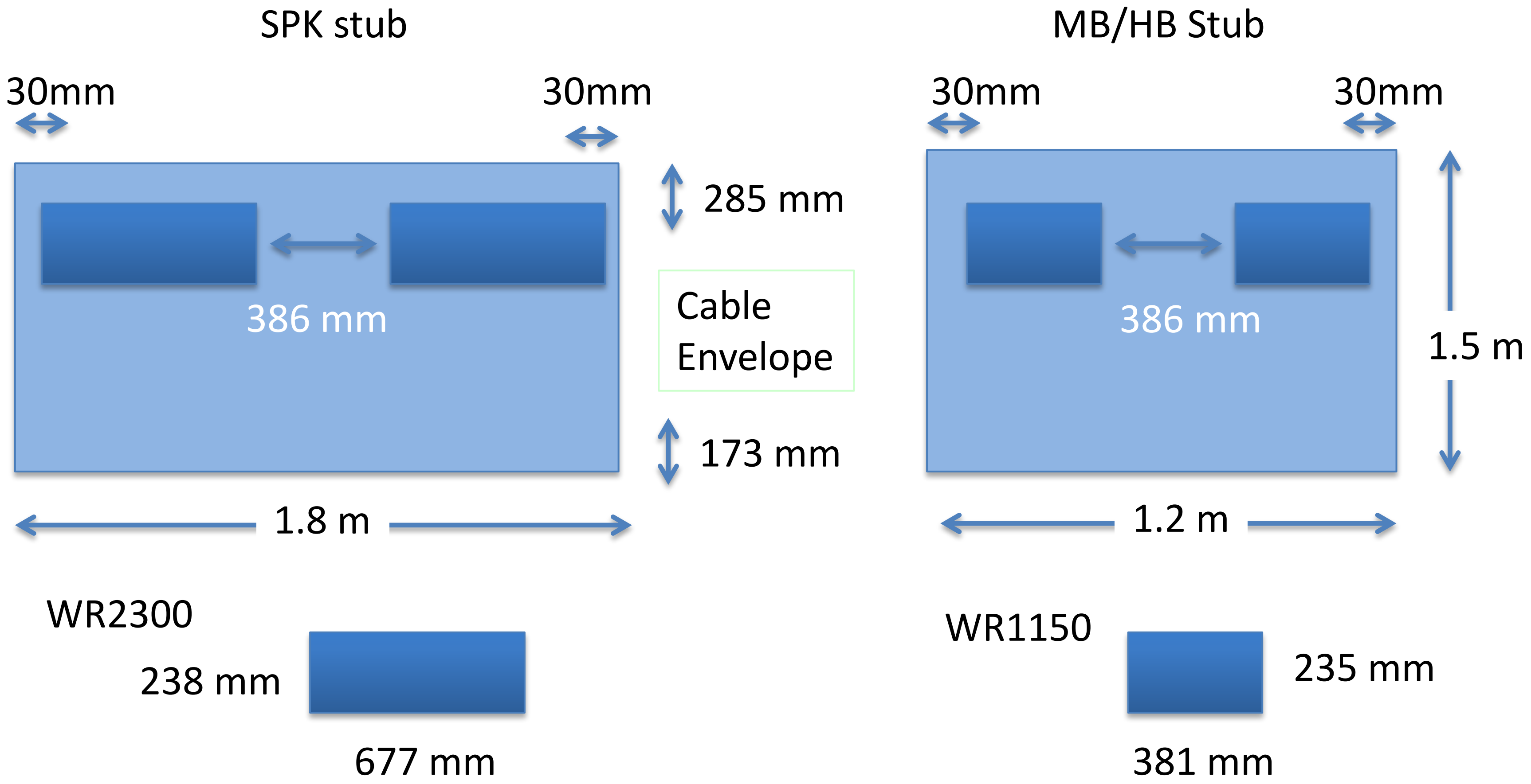


# Stub Mockup with wooden waveguides and stub



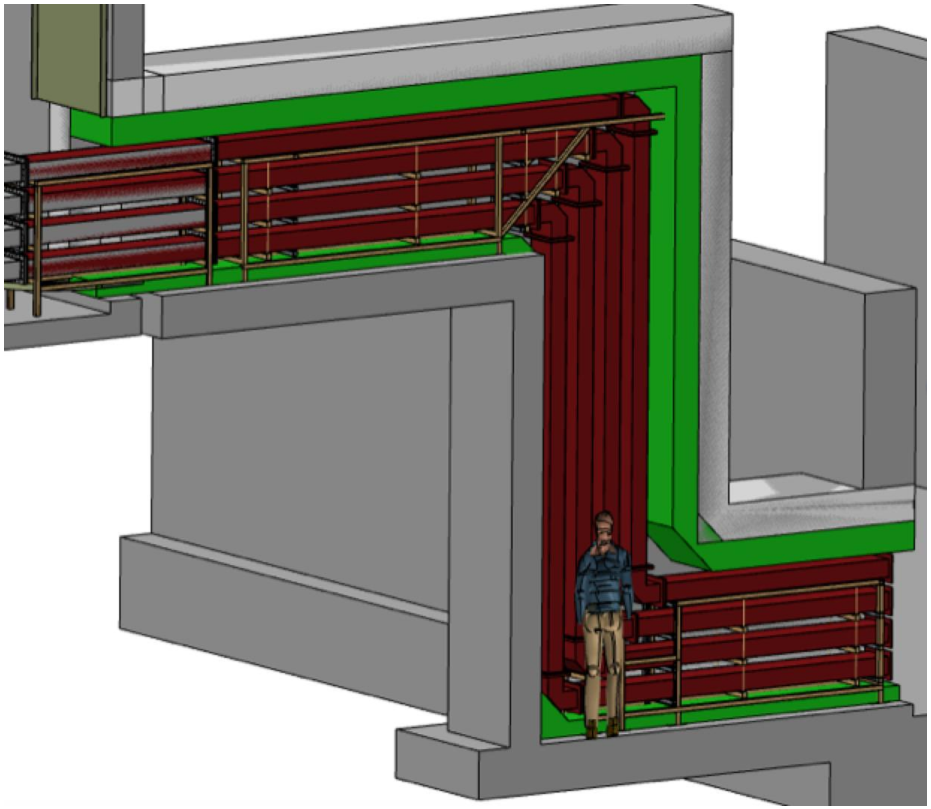


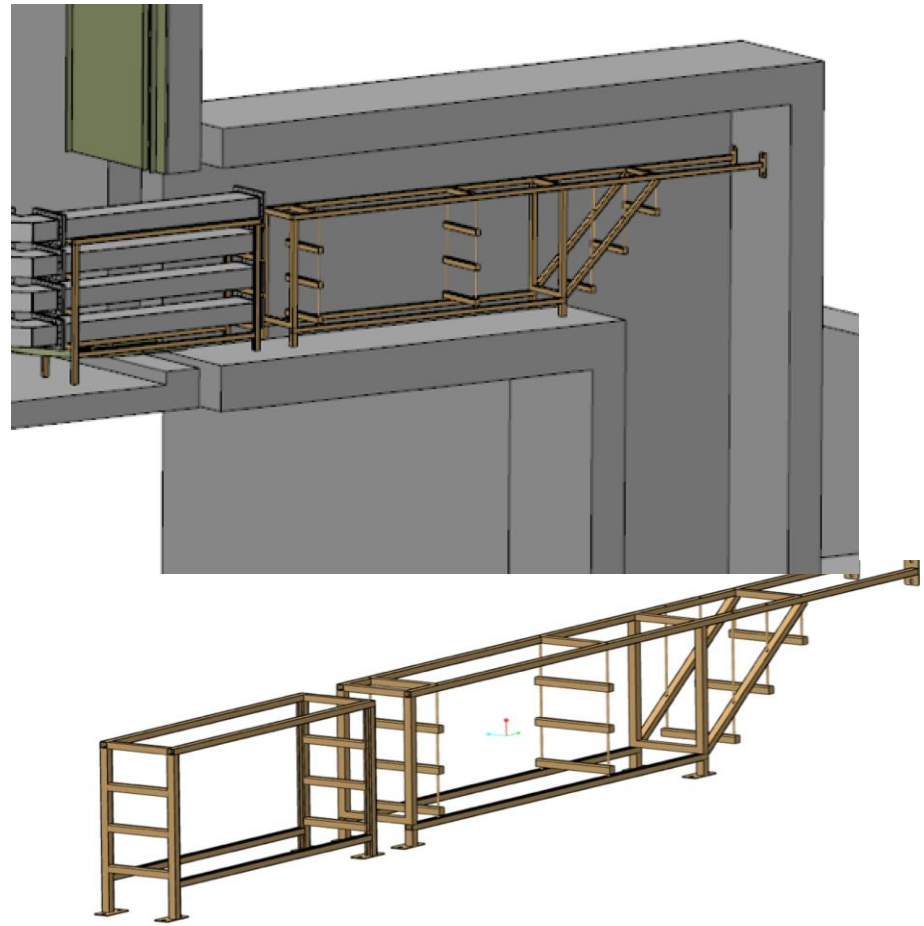
# Stub Installation: Difficulties and Mitigation




- So installation is very difficult for SPK stub
- Full test mock up is planned in Jan 2017 using the actual stub

# Preliminary concept for the Stub Support Structure





- Prototype under construction.
- Will be tested in test stub mockup at ESS site in Jan 2017.

# Thank you !