High Power Model of Isolator

Rutambhara Yogi

Many thanks to

- ✓ Suppliers:

THALES

Ferrite Microwave Technologies

AFT microwave

Exir Broadcasting

MEGA RF Solutions INDUSTRIES, LLC

- ✓ Colleagues:

ESS: Mats Lindroos, David McGinnis, Anders Sunnesson, Morten Jensen,
A. Johansson, Carlos Martins, Rihua Zeng, Rafael Montano, Chiara Marrelli,
Stevo Calic, Bruno Lagoguez, Staffan Ekström, Daniel Lundgreen, Carl Johan Hardh

FREIA: Rolf Wedberg, Lars Hermansson, Roger Ruber, Magnus Jobs & other colleagues

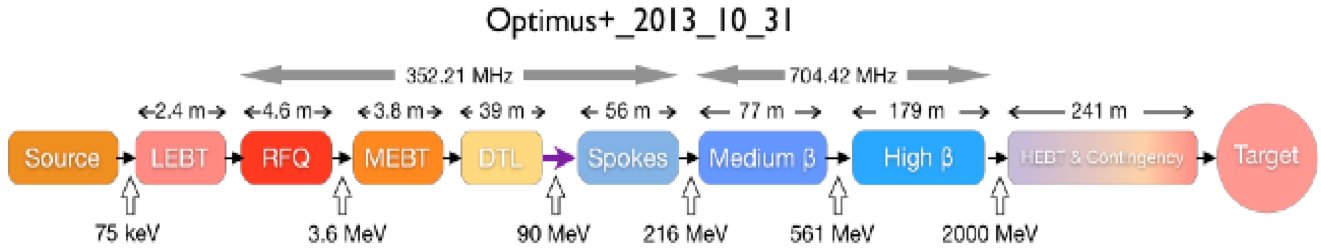
CERN: Eric Montesinos, Olivier Bruner

SNS: Crofford Mark

Outline

- Brief introduction to ESS RF systems
- Circulator
- High power model of Isolator
- Effect of hot water cooling

ESS: European Spallation Source

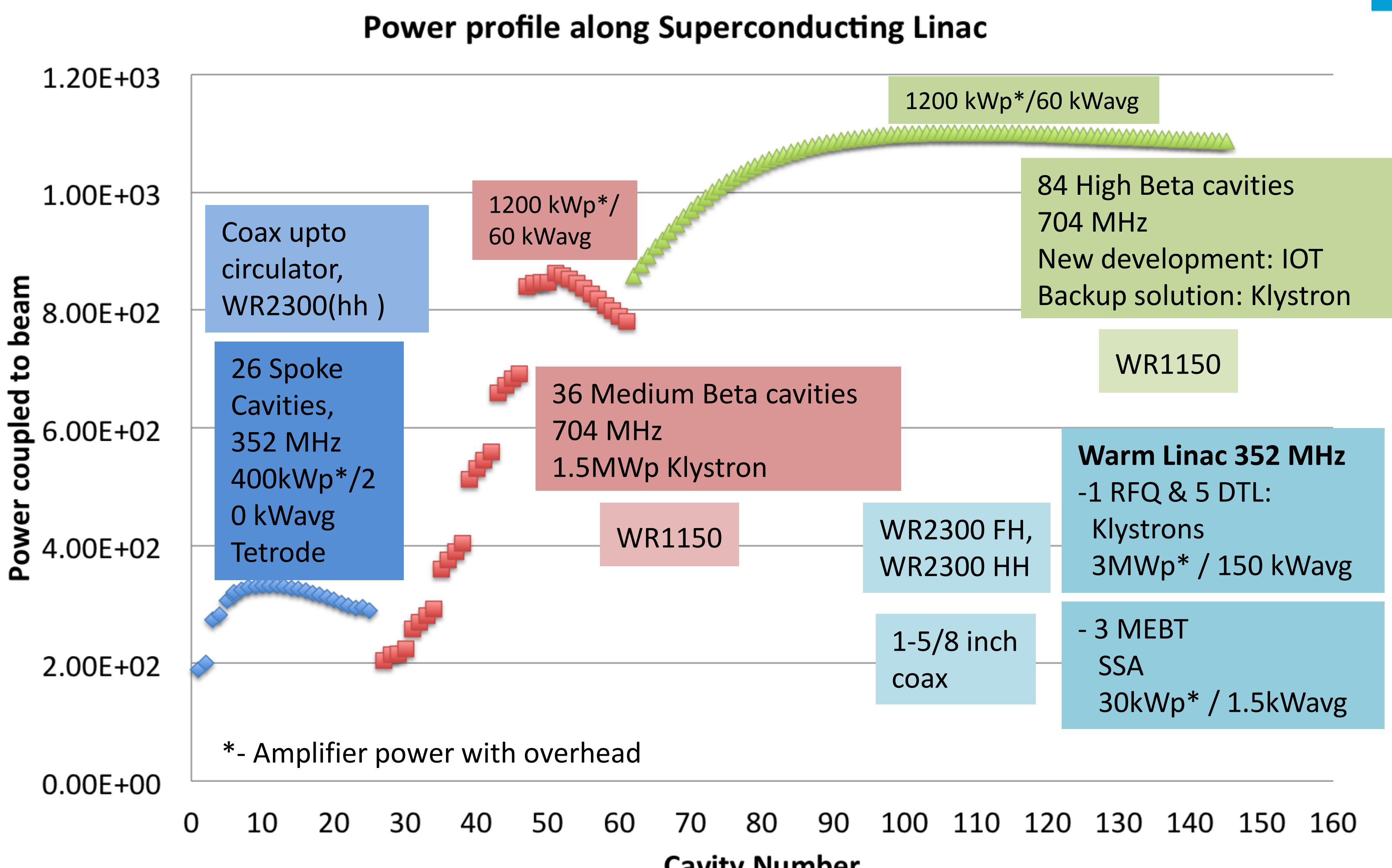


- Beam pulse width = 2.86 ms
- Pulse repetition rate = 14 Hz
- Peak proton beam power to the target = 125MW
- Most intense pulsed neutron source in the world : peak beam power larger by factor 5 compared to existing spallation facilities

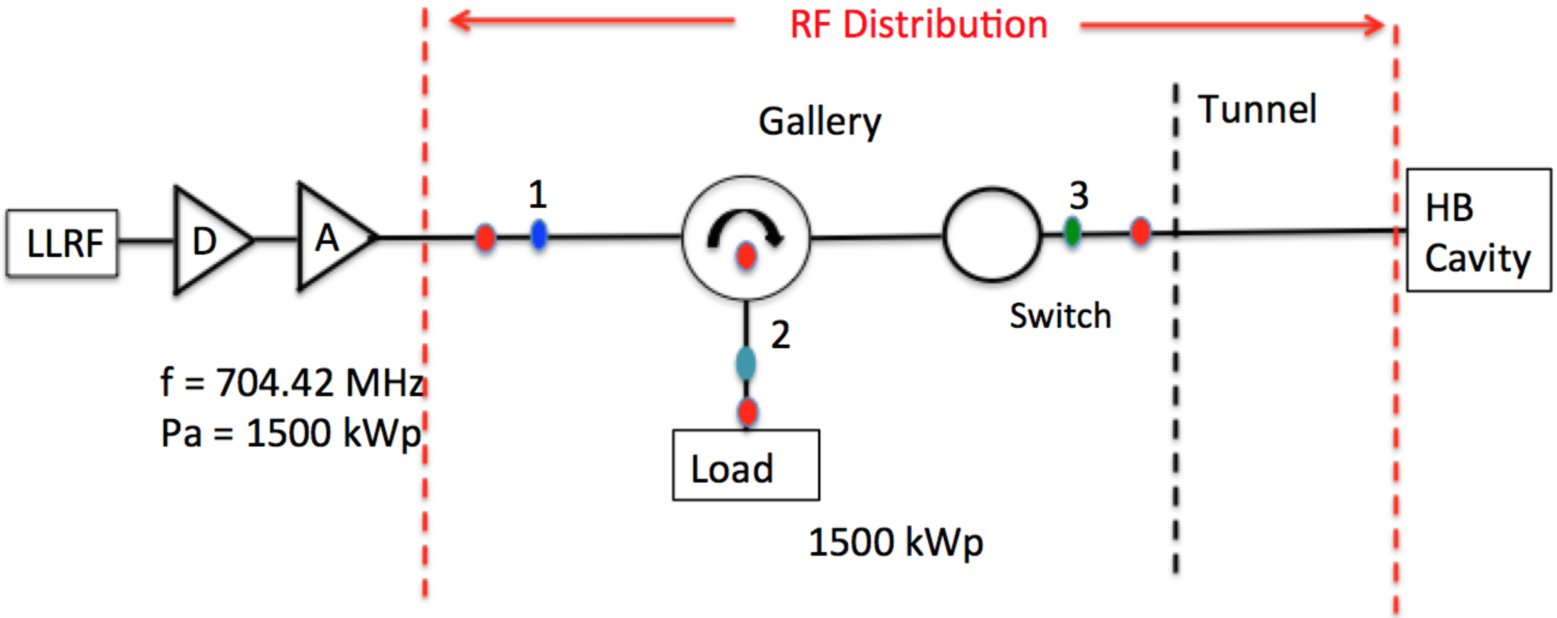
Europe's one of the largest infrastructure

Being constructed in Lund, Southern Sweden

Power profile

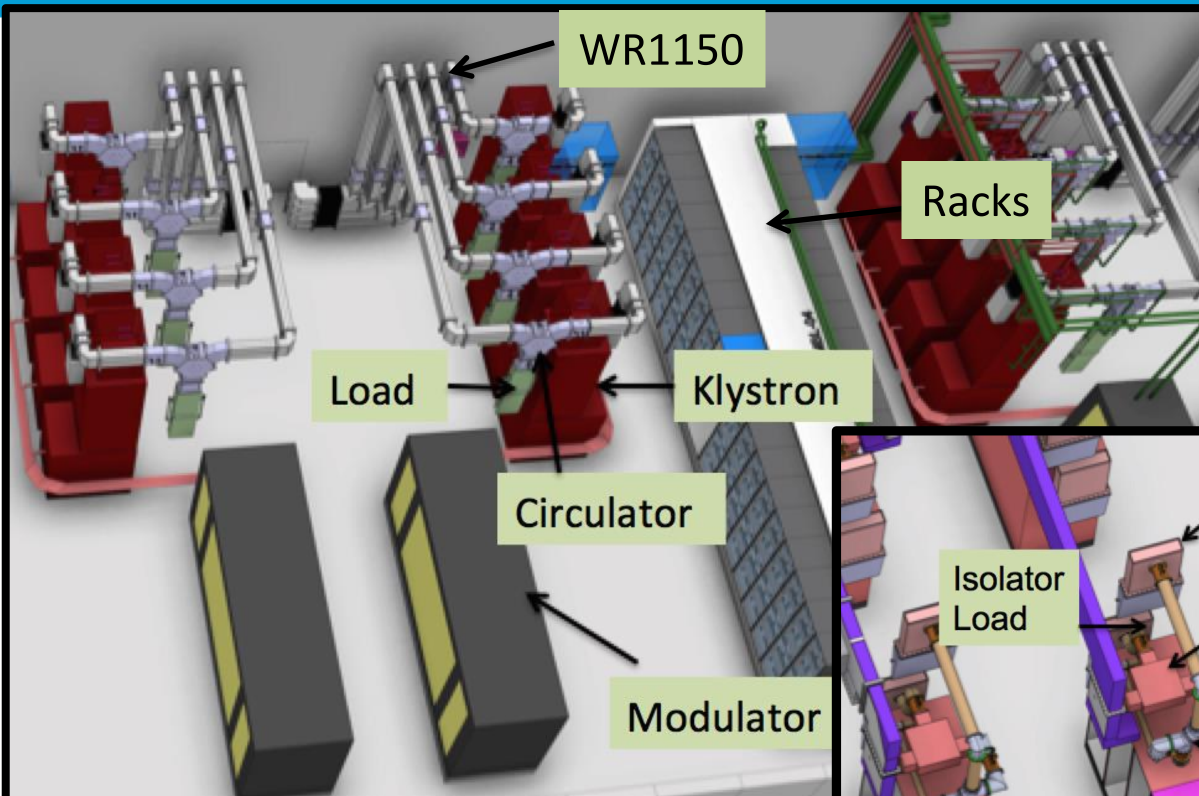


Schematic of RFDS for MB/HB

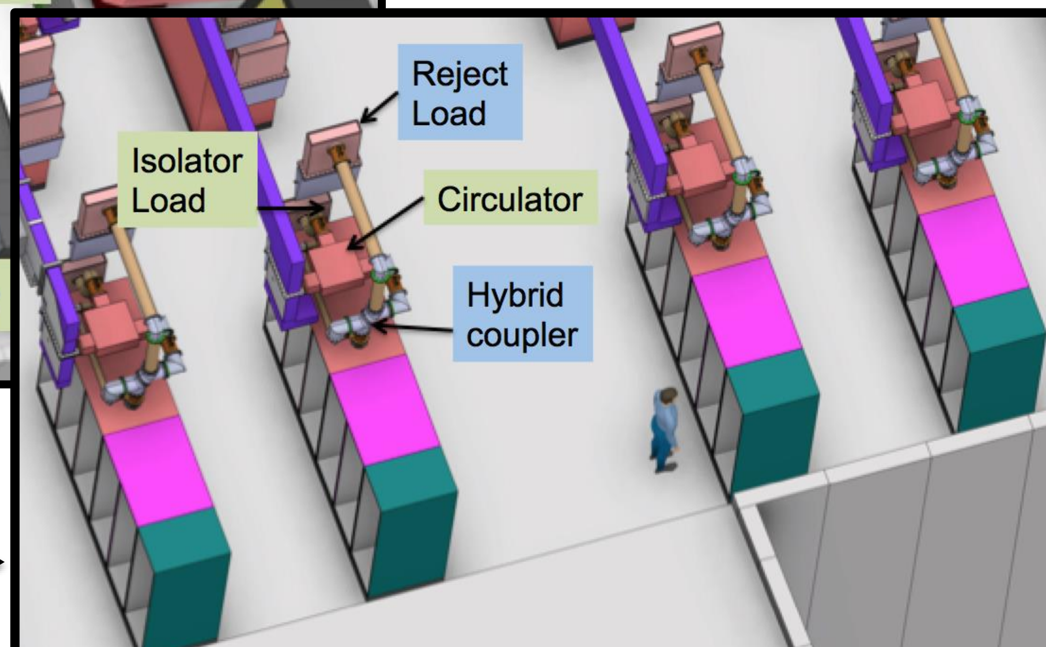


D – Driver
A – Amplifier (klystron/IOT)
- DC (directivity > 40 dB, 4 loops)
- DC (directivity > 30 dB, 4 loops)
- DC (directivity > 30 dB, 2 loops)
- Location of Arc detectors
- Waveguide, bends (E and H), flexible waveguides

DC used for LLRF:1(F,R),3(F,R)
DC used for interlocks:1(F,R),3(F,R)
DC used for diagnostics 1 (F,R), 2(F,R), 3(F,R)

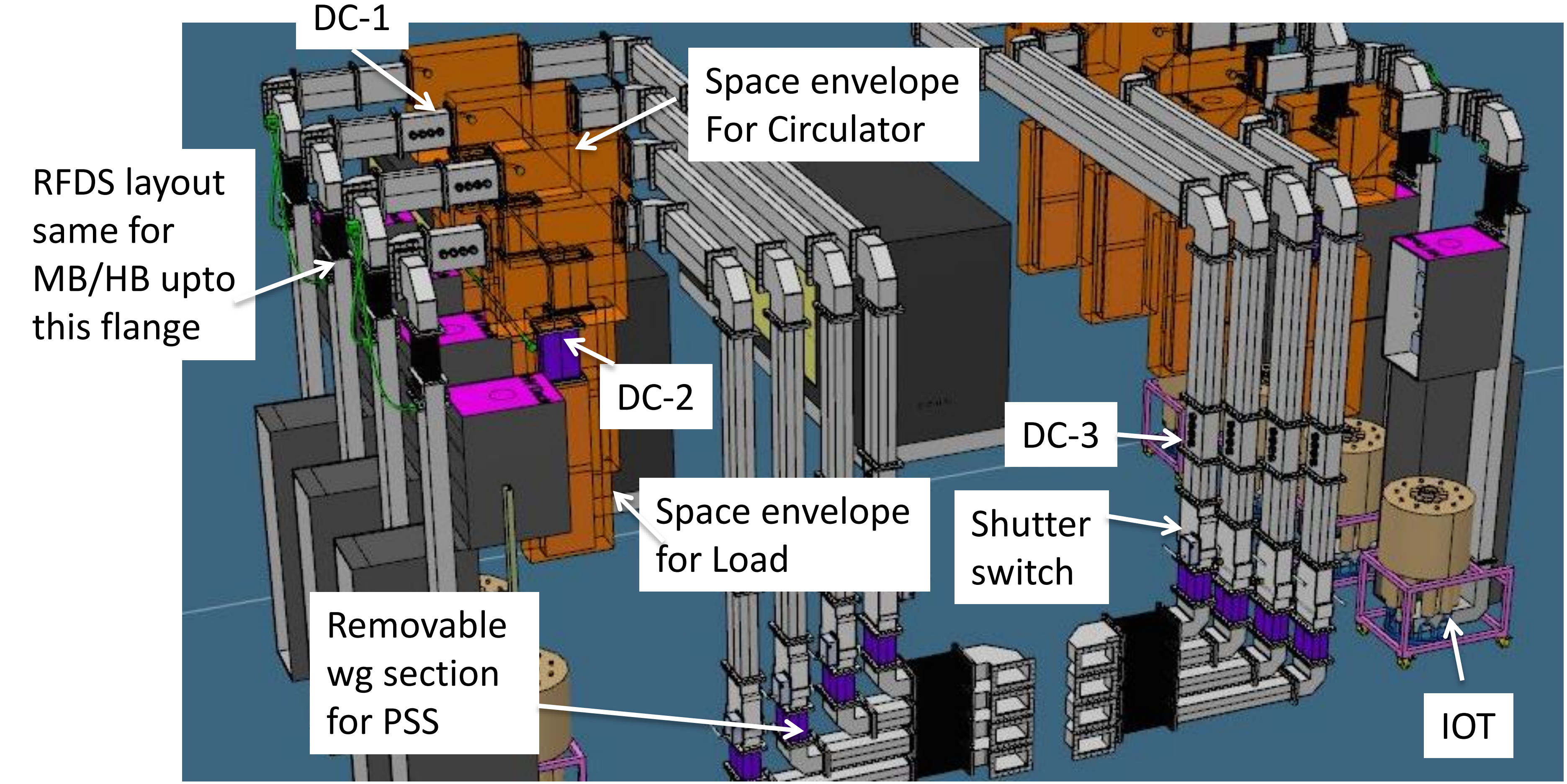


Gallery layout MB cell



Gallery layout for Spokes

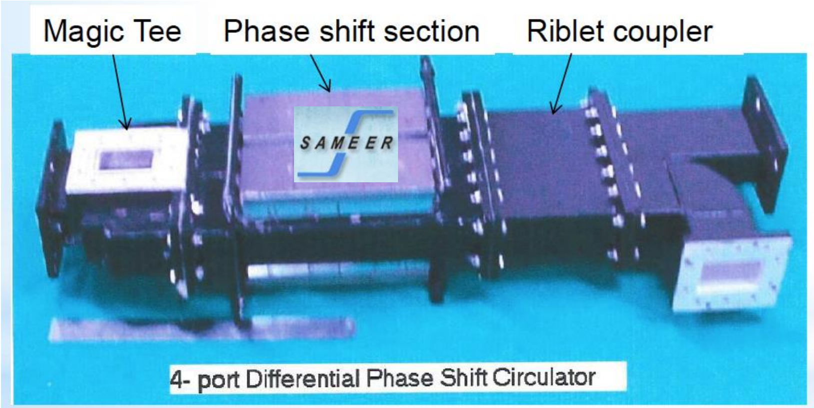
RFDS layout for HB / MB cell



Circulator

Ideal Circulator: Like a round about

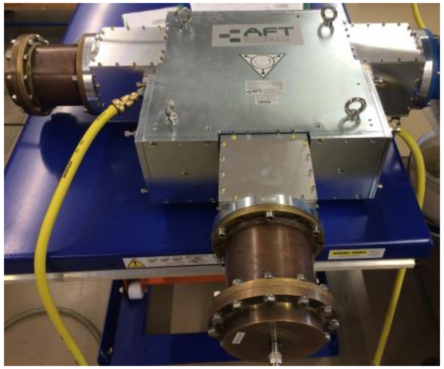
2.856 GHz
P = 6 MWp
Pavg = 25 kW



Indigenous development done at SAMEER (India) in 1999. Installed on medical linac.

- Can have either 3 ports or 4 ports
- Can use coaxial line / waveguide
- Direction – clockwise / anti-clockwise

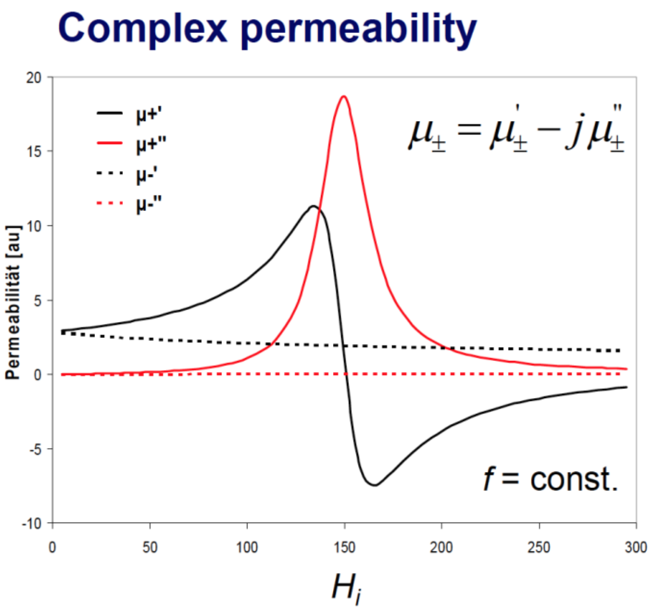
352 MHz
P = 400 kWp
Pavg = 20 kW

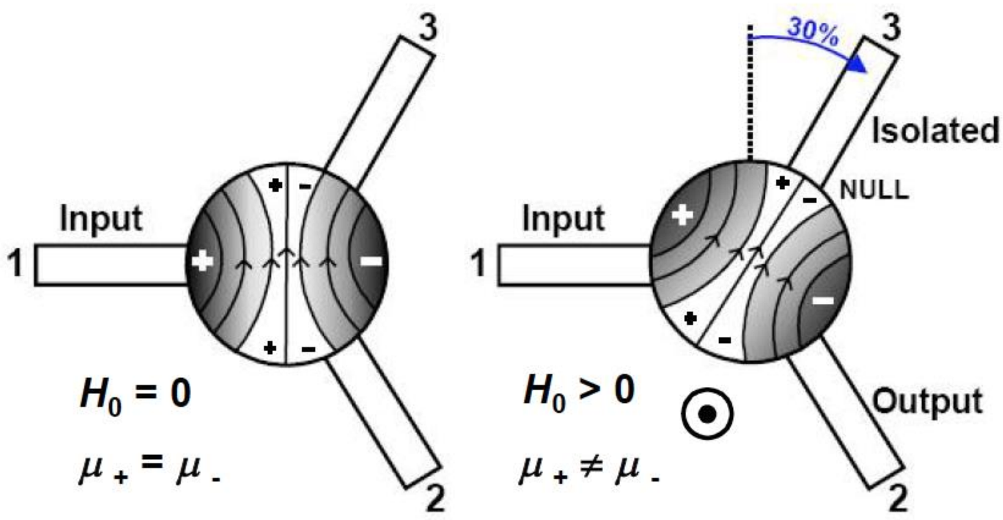


Technology demonstrator for ESS spoke linac

Circulator

- Nonreciprocal device
- Non-reciprocity is achieved due to ferrite
- Generally ferrite discs are used
- The discs can be either two discs or the multiples of two. Depends on power and thermal management
- Difference in μ_+ and μ_-, leads to non-reciprocity





RF signal applied to the ferrite disc will generate two counter rotating waves, velocity dependent on propagation direction.

$$\beta_{\pm} = \frac{\omega}{c} \cdot \sqrt{\varepsilon \mu'_{\pm}}$$

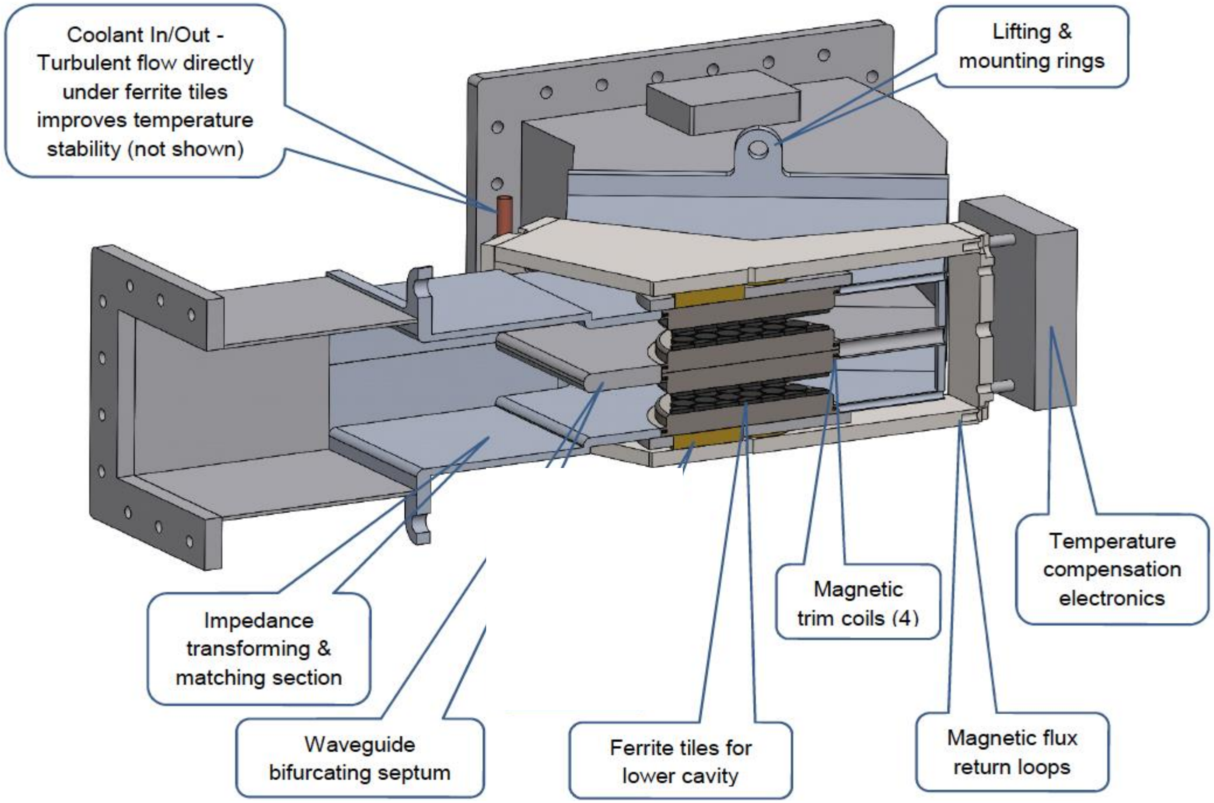
Transmission
from port 1 to port 2

$$2\beta_{+}\ell - \beta_{-}\ell = \pm 2N\pi$$

Isolation
From port 1 to port 3

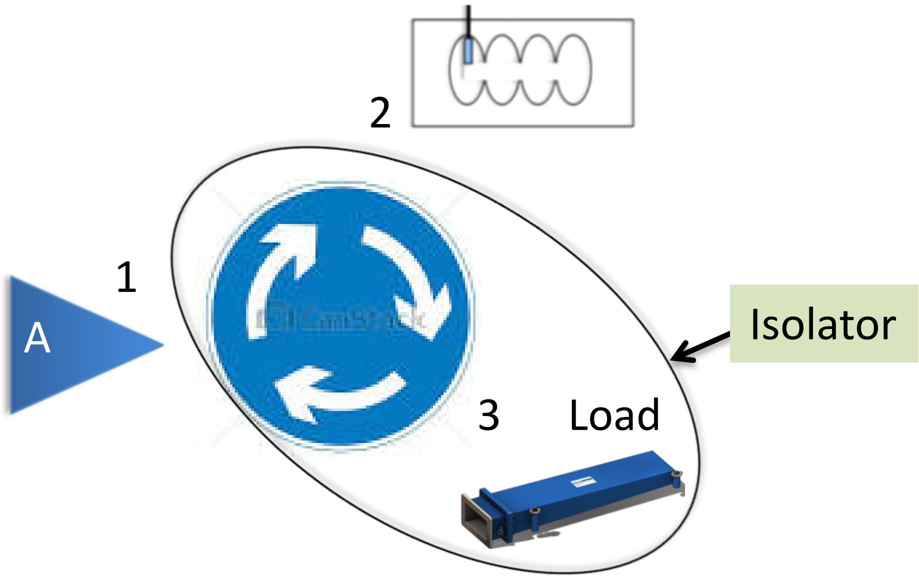
$$\beta_{+}\ell - 2\beta_{-}\ell = \pm(2M-1)\pi$$

Construction of 3-port Circulator



Ideal & Practical Isolator
Isolator = Circulator + load

Ideal: Infinite Isolation



Load – Dissipate RF power from amplifier

Amplifier is completely isolated from unwanted reflections

Practical: Finite Isolation

Isolation = - 30 dB

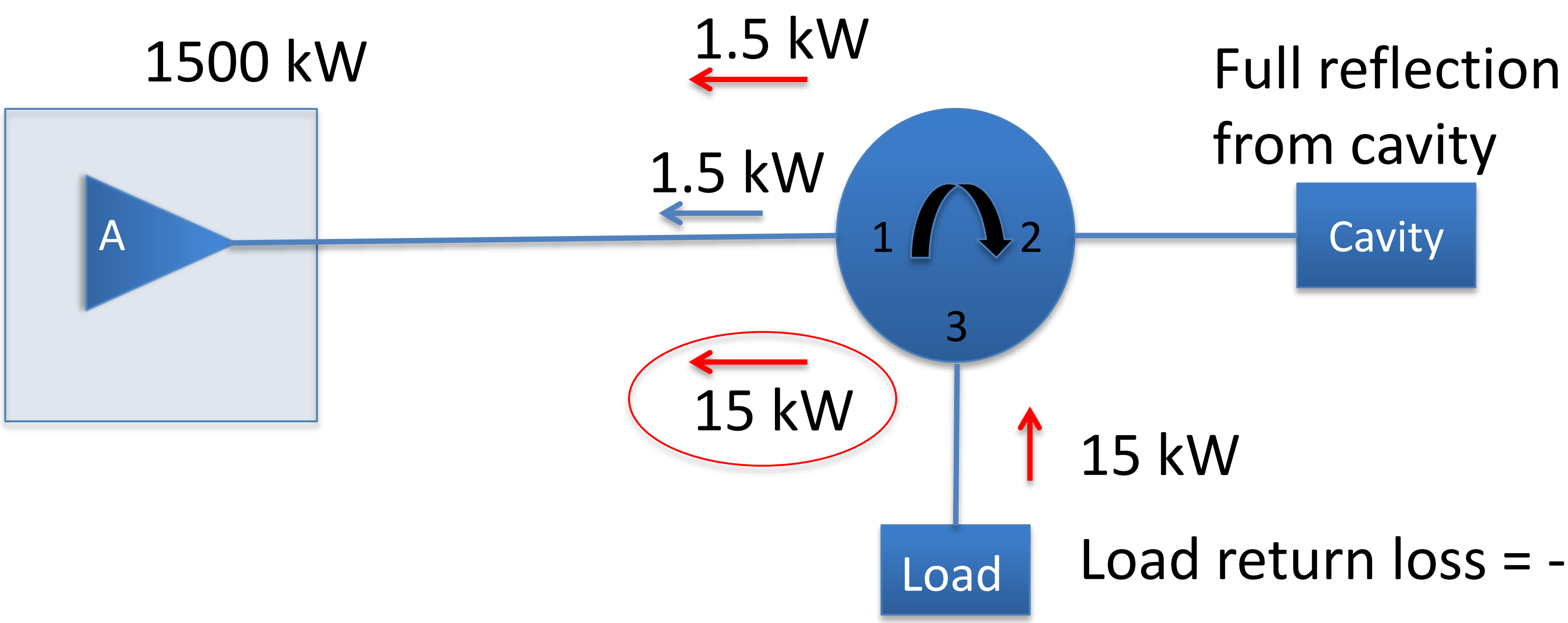
Input power = 1500 kW

Only 1500 W = 1.5 kW will reach amplifier ?

Practical Isolator:

Isolation = 30 dB

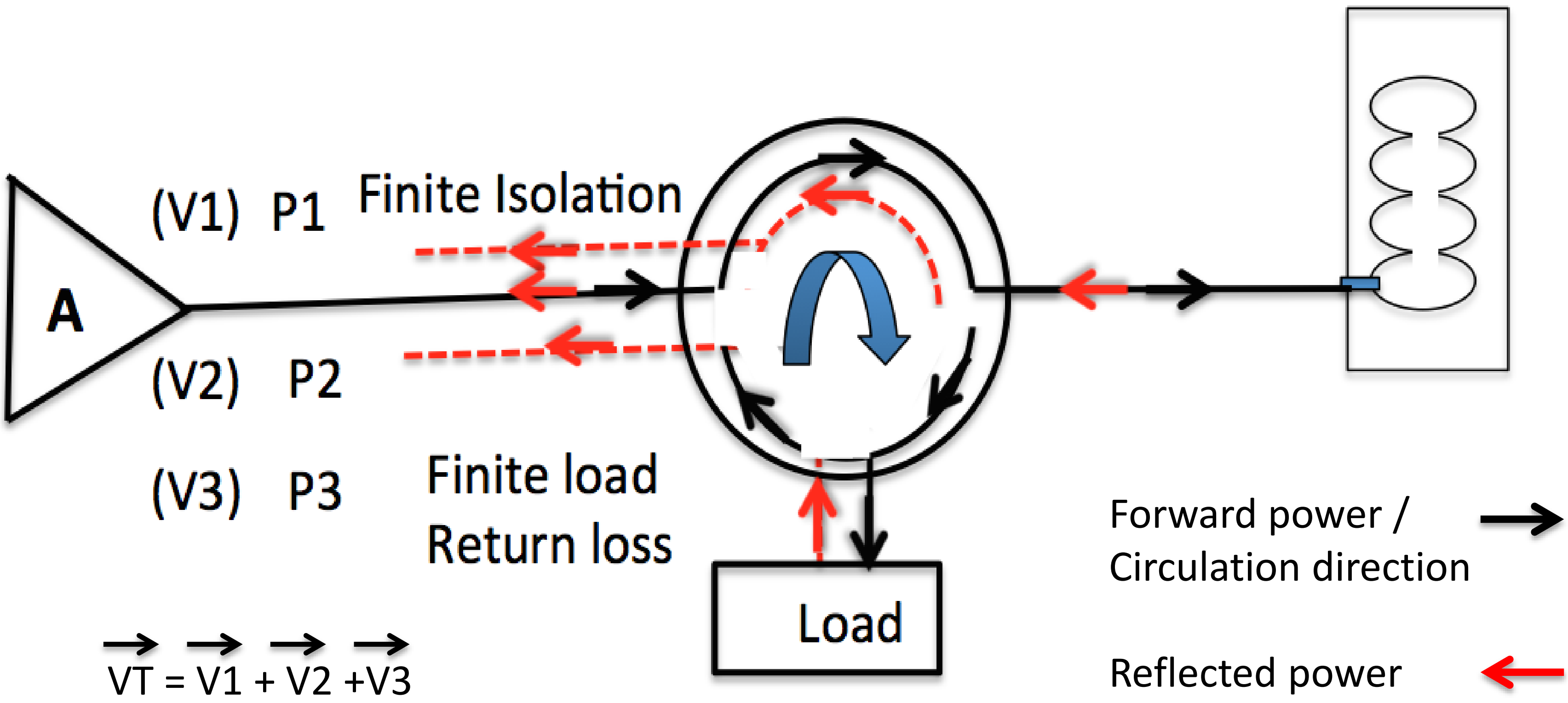
Return loss = 30 dB



Load return loss = - 20 dB

So we need a load with good Return loss

High Power Model of Isolator

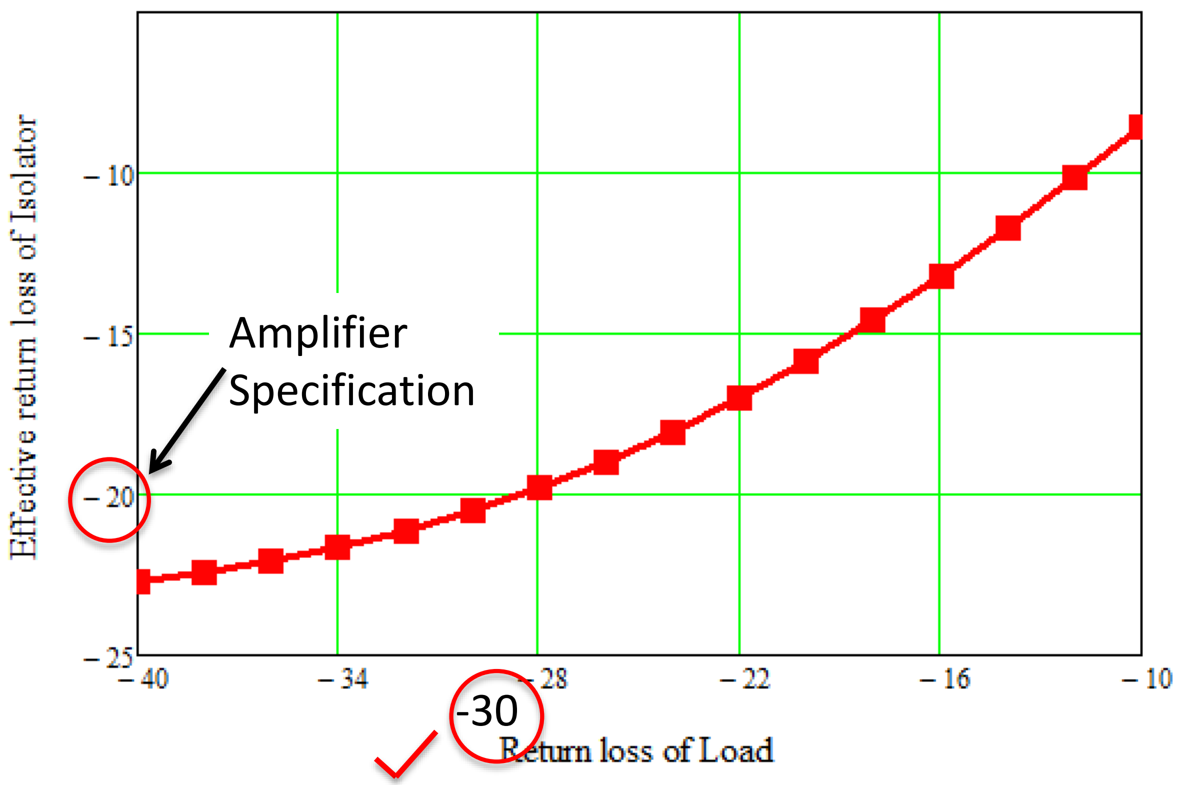


A small program is written for effective return loss calculation (Ref: ESS-0043091)

Assumptions:

- Amplifier is perfectly matched.
- Higher order harmonics are not considered
- Uncertainties in S-parameter measurement not considered
- Only first order reflections are considered
- Worst case S-parameters and worst phases for S11eff calculations are considered.

Variation of Effective return loss of Isolator with return loss of load



Parameters of circulator :

S11= -30 dB

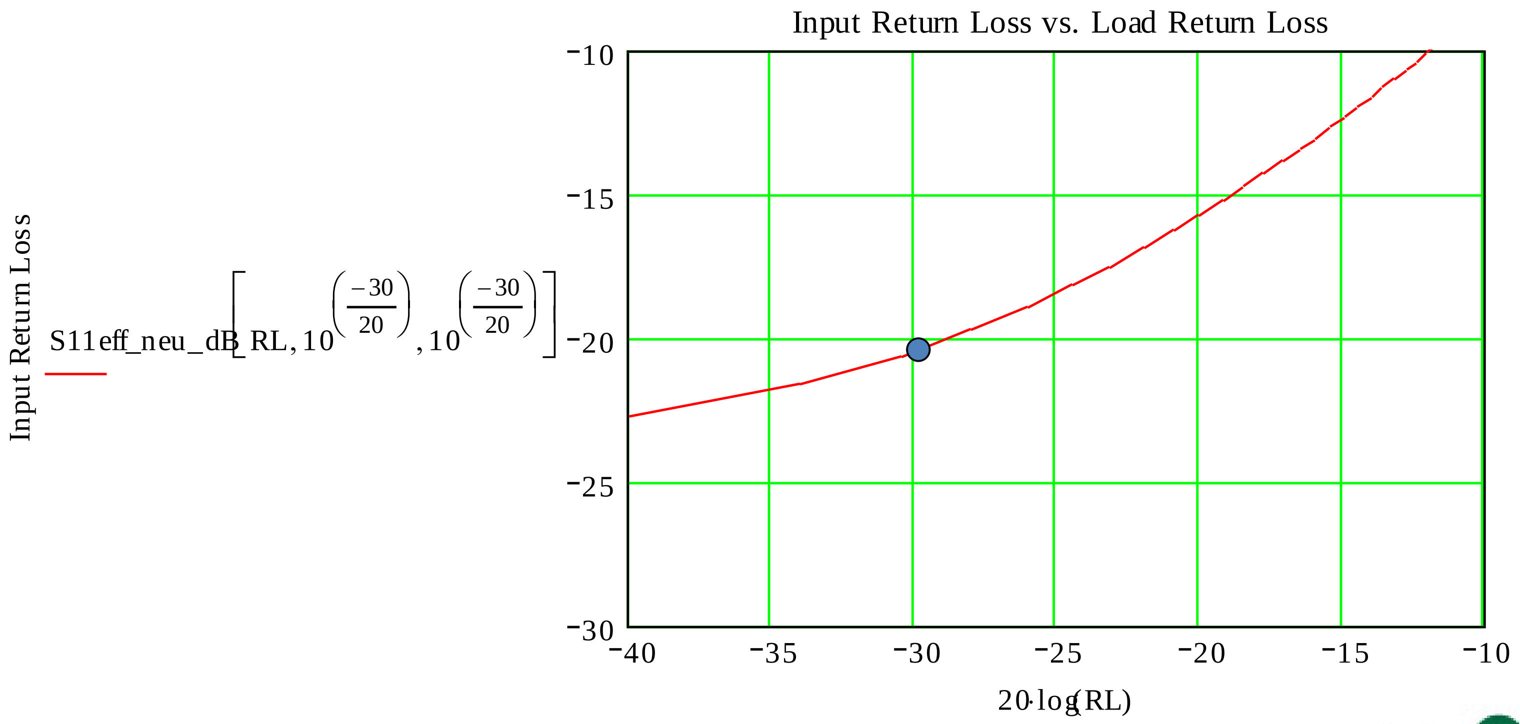
S12 = -30 dB

S21 = -0.5 dB

NO higher order harmonics

We need a GOOD LOAD:

Worst Case Input Return Loss $|S_{11eff}|$ for $|S_{11}| = |S_{12}| = 30dB$ (typical)



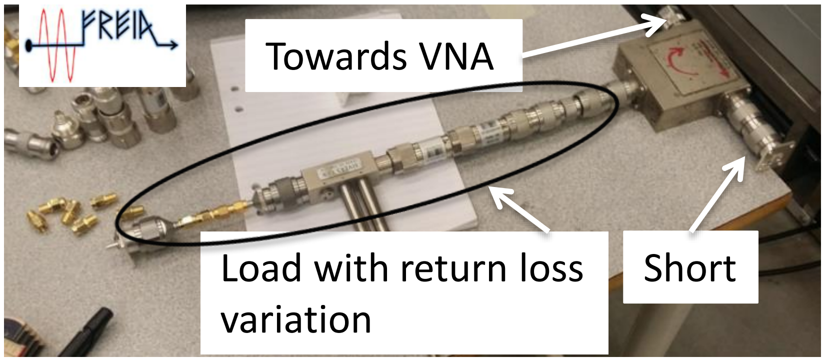
Variation of Effective return loss of Isolator with Phase of load return loss

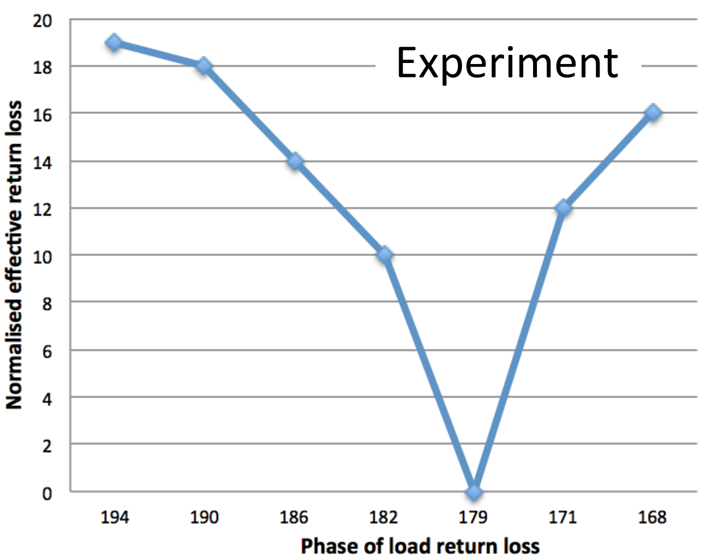
Parameters of Circulator:
S11 = -30 dB
S12 = -26 dB
S21= -0.05 dB

Parameters of Load:
S11 = -30 dB

Value is not important.
Phase of load return loss: stable
Waveguide section can be added to get desired phase shift

Testing of concept





Courtesy: Magnus Jobs at FREIA

- Trend of both the curves is same
- Good return loss when phase of load return loss at circulator is about 180 °

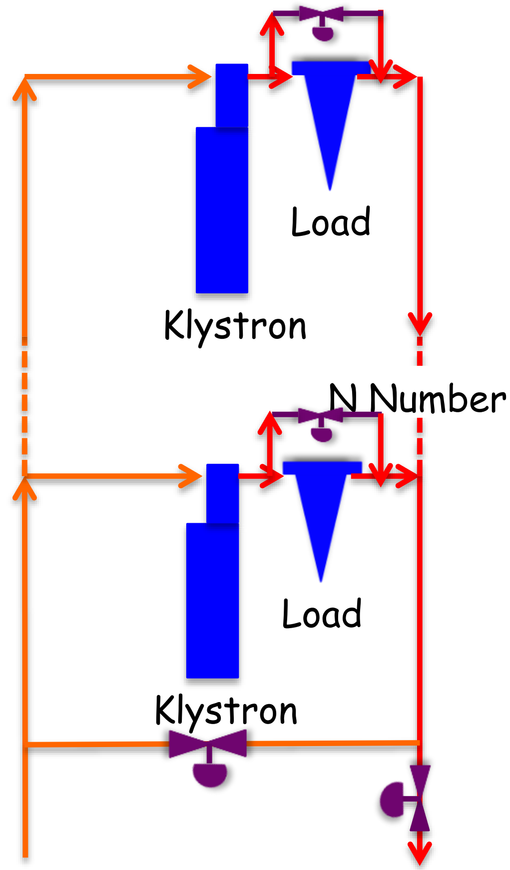
Further experimentation is planned with high power Circulator and load at Lund test stand.

Additional boundary conditions in ESS: High temperature water cooled loads

Temperature rise due to power dissipation across collector:

With HV on, RF off:
$\Delta T \sim 10\ ^{o}C$

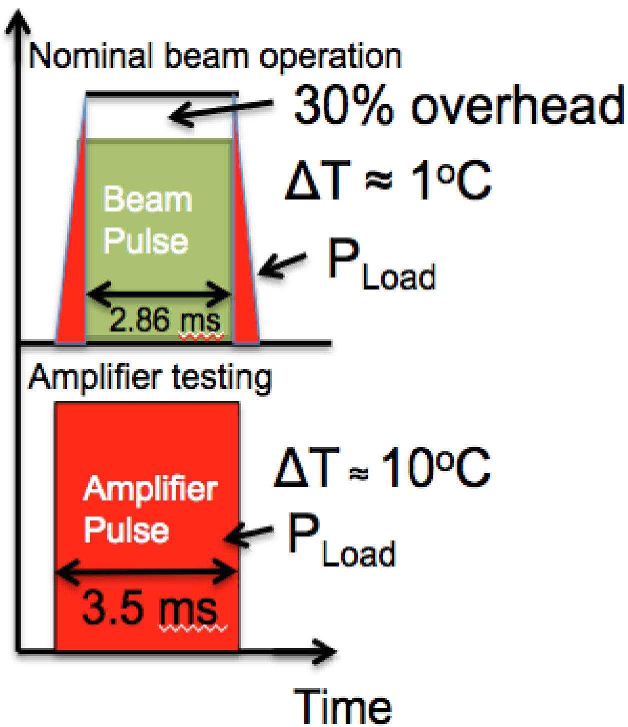
With HV on, RF on:
Nominal beam operation,
Klystron testing,
$\Delta T \sim 5\ ^{o}C$



Inlet temp 50°C

Initially Outlet temp Controlled to 60°C

Power dissipated across load



Effect of unstable phase of load return loss

\# Klystron operation will be affected

- At same power level, cooling water temperature will vary from 50º C – 80º C depending upon operational scenario.
- If phase of load return loss also varies, S11eff seen by amplifier will vary automatically, which may affect klystron stability.

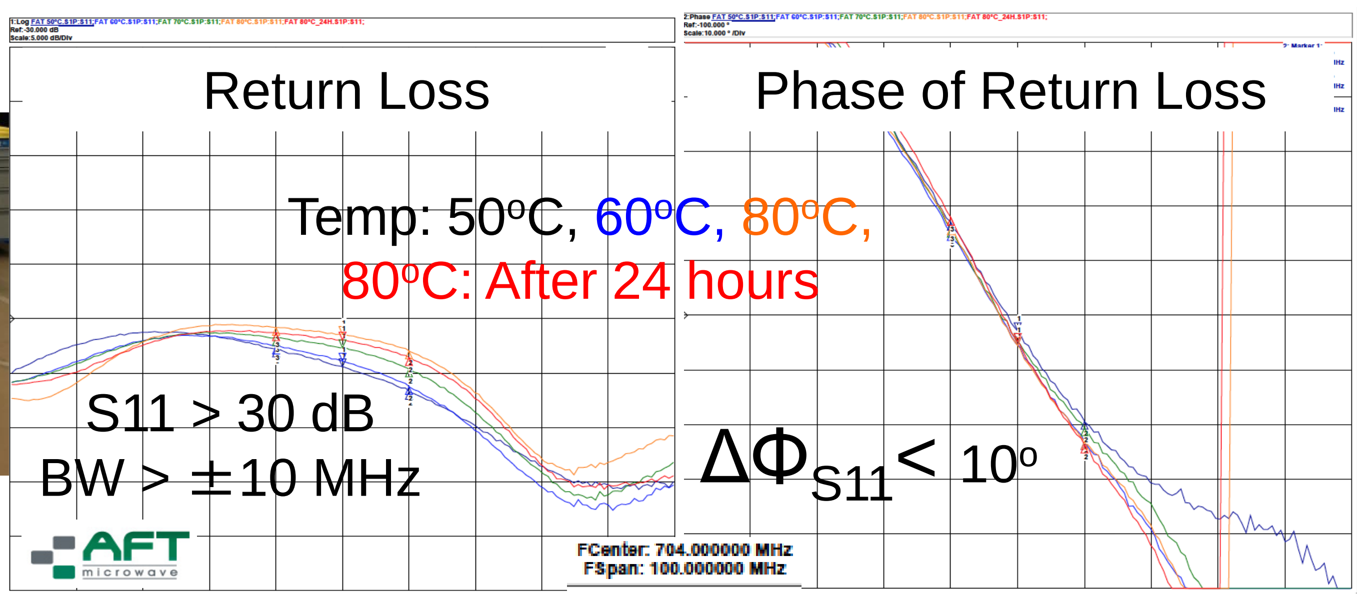
Hence stable phase of load return loss will be preferred.

New Load development for ESS
Hot water cooled loads

EUROPEAN SPALLATION SOURCE

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



Prototypes by MEGA, Thales will be delivered soon.

Thank you !

Functional Requirements of RFDS

- Transportation of RF power from amplifier to the cavity coupler with minimum losses
- Dissipation of unwanted RF power during different operational scenario - **Loads**
- Protection of amplifier from the unwanted reflections during filling and emptying of cavities or due to sparks – **Circulator**
- To satisfy requirements of personnel safety system (PSS) during different operational scenarios – **removable waveguide, PSS flange, switch**
- Detection of sparks in the RF system and give signal to the local protection system (LPS) – **Arc Detectors**

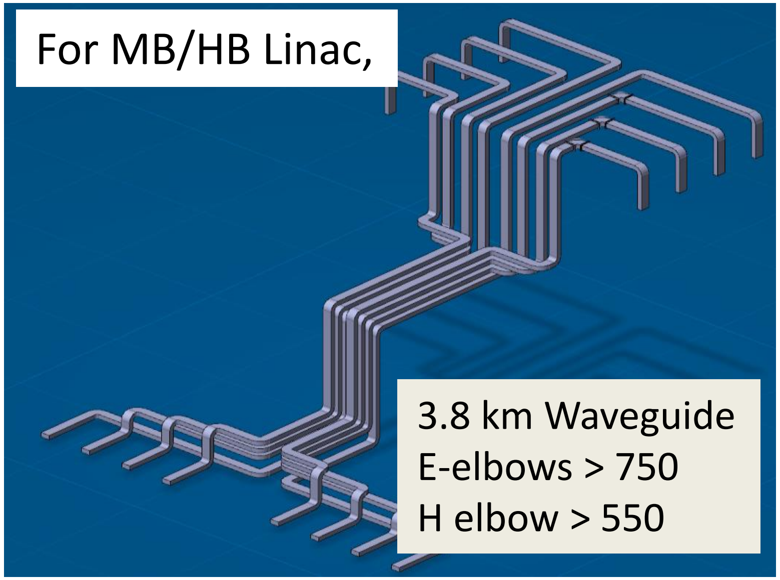
- Measurement of forward and reflected power from amplifier and cavity with the required accuracy, granularity - **Directional couplers**
- Take care of thermal expansion-contraction, dimensional changes in building layout such as changes in the tunnel length, differential settlement of tunnel with respect to gallery etc – **Bellows**
- Simplification of cooling system design for energy recovery – **High temperature water cooled loads**
- Depending on requirement, to ensure stable klystron operation by changing distance between klystron and circulator – **extra flanges**

Prototype RFDS at ESS

Hot water cooled loads – New development for ESS
Being developed by three suppliers: AFT, MEGA and Thales
Received AFT load in Lund test stand,
MEGA and Thales load will be shipped by end of July / August

Circulators being developed by three suppliers: AFT, MEGA and FMT
FMT circulator will be shipped in a few days.
DR for MEGA circulator: 27 June
AFT circulator: Expected delivery by Aug end.

High directivity directional couplers (D > 40 dB)- by MEGA



Huge requirement of waveguides and elbows !

Flange and waveguide design

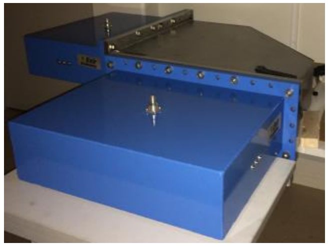
Waveguide extends through the flanges

Fabrication becomes extremely easy and avoids discontinuities

- Flanges will be welded along the periphery (*)
- Surface cut along flange surface to ensure flatness, perpendicularity and parallelity
- Flat flanges (without RIM)
- Time spent at ESS < 20 hours.

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

Received prototypes from two companies.



Arc Detectors (AD)

Procured two types of Arc Detectors

- AFT : uses optical fibre, response time < 10 µs

- Microstep/CERN AD – don't need optical fibre

  * Four redundant photodiodes: to detect spurious arcs

  * Two blind photodiodes: to detect radiation induced arcs

Tests will be performed in the Lund test stand and then preferred solution will be selected.