LH engineering introduction

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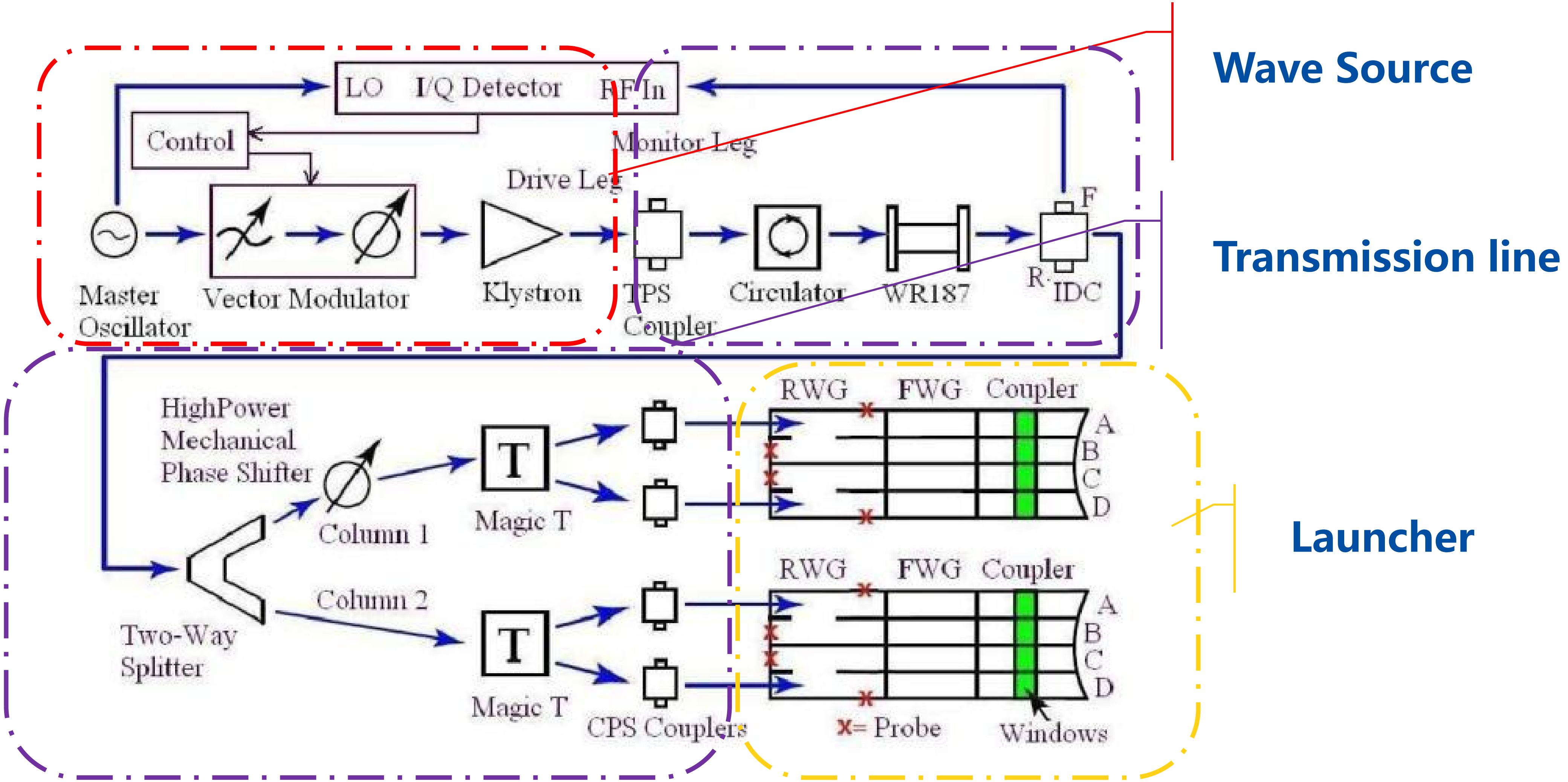
CONTENTS

Brief introduction of LHCD

- □ LHCD: Lower Hybrid Current Drive
- ● The most efficient method for current drive
- ● Important in the long pules duration plasma operation for tokamak devices
- □ LHCD technology development history:
- ● before 1970s: early experiments on small devices, applied for heating at first with indivdual WGs
- ● 1980s ~ 1990s: applied for CD on ALCATOR C-Mod, Tore Supra and JET with developed antenna (Multijunction)
- ● 2000s ~ 2010s: Passive-Active Multijunction antenna applied on FTU, Tore Supra, even to H-mode plasma on HL-2A
- ● 2020s: HFS antenna developed on DIII-D
- □ LHCD is widely used on tokamaks

LHCD composition



LHCD system of ALCATOR C-Mod

CONTENTS

General introduction

□ Parameter of LHCD system

- Frequency 1-10GHz: mainly 2.45GHz(EAST), 3.7GHz(WEST/Tore Supra/HL-3/JET), 4.6GHz(EAST/ Alcator C-Mod), 5GHz(ITER/KSTAR, designed), 8GHz(FTU)
- Power: 1-16MW

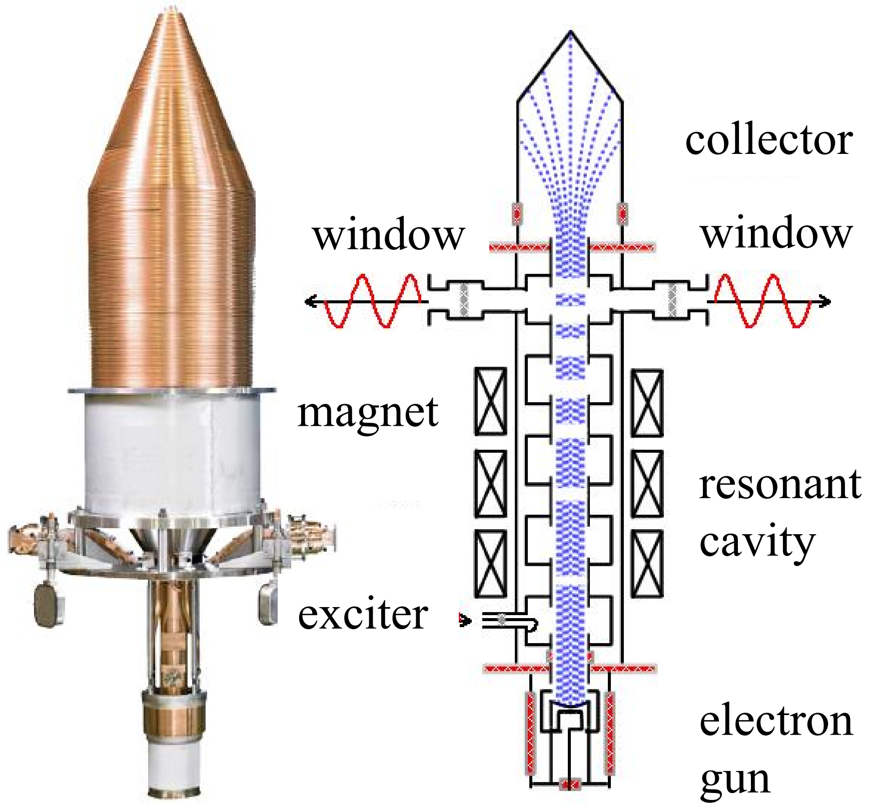
□ Key equipment of LHCD wave source

- Klystron: for most of the LHCD systems on tokamaks
- Gyrotron: for FTU in Italy

Klystron & Gyrotron

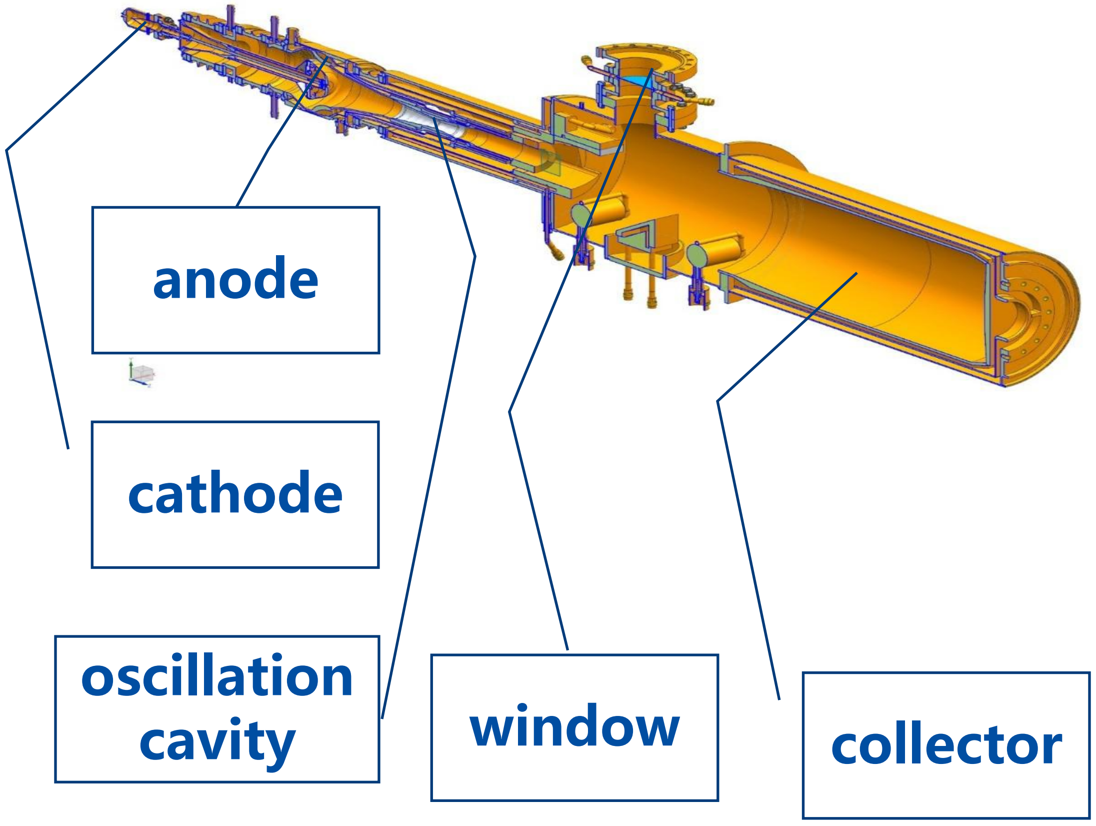
Klystron: RF amplifier

- introduce here

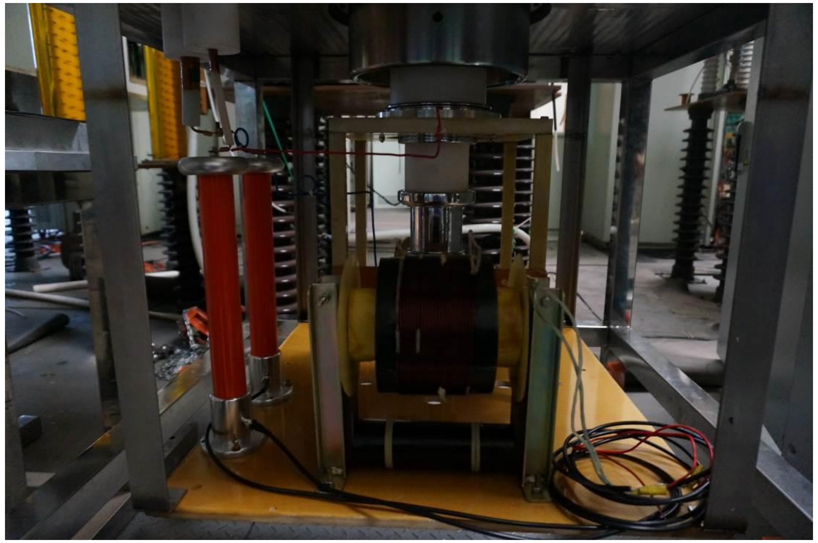


Gyrotron: Oscillator

- mostly applied for ECRH, introduced yesterday



Auxiliary system —— magnet and support



☐ Magnet

- Provide a magnetic field of ~10^2mT
- Supporting the Klystron
- Water cooling needed

☐ Support

- Mainly a box, some are filled with oil
- Cathode connector in
- Filament PS isolation transformer in
- Voltage divider for HV measurement in

Auxiliary system —— Power supply

- **Filament PS**
  - Heater < 1kW to make the cathode release electrons
  - Isolated from the PS via a transformer (AC)
  - Rising and landing slowly

- **Titanium Sublimation Pump PS**
  - HVPS ~DC 5kV, I~ 1μA-10mA
  - Different channel with different range of the current needed
  - Operated in long term

- **Magnet PS**
  - Constant current PS: DC
  - I~20-40A could be fine controlled (0.01~0.1A)
  - High requirement on ripple and stability

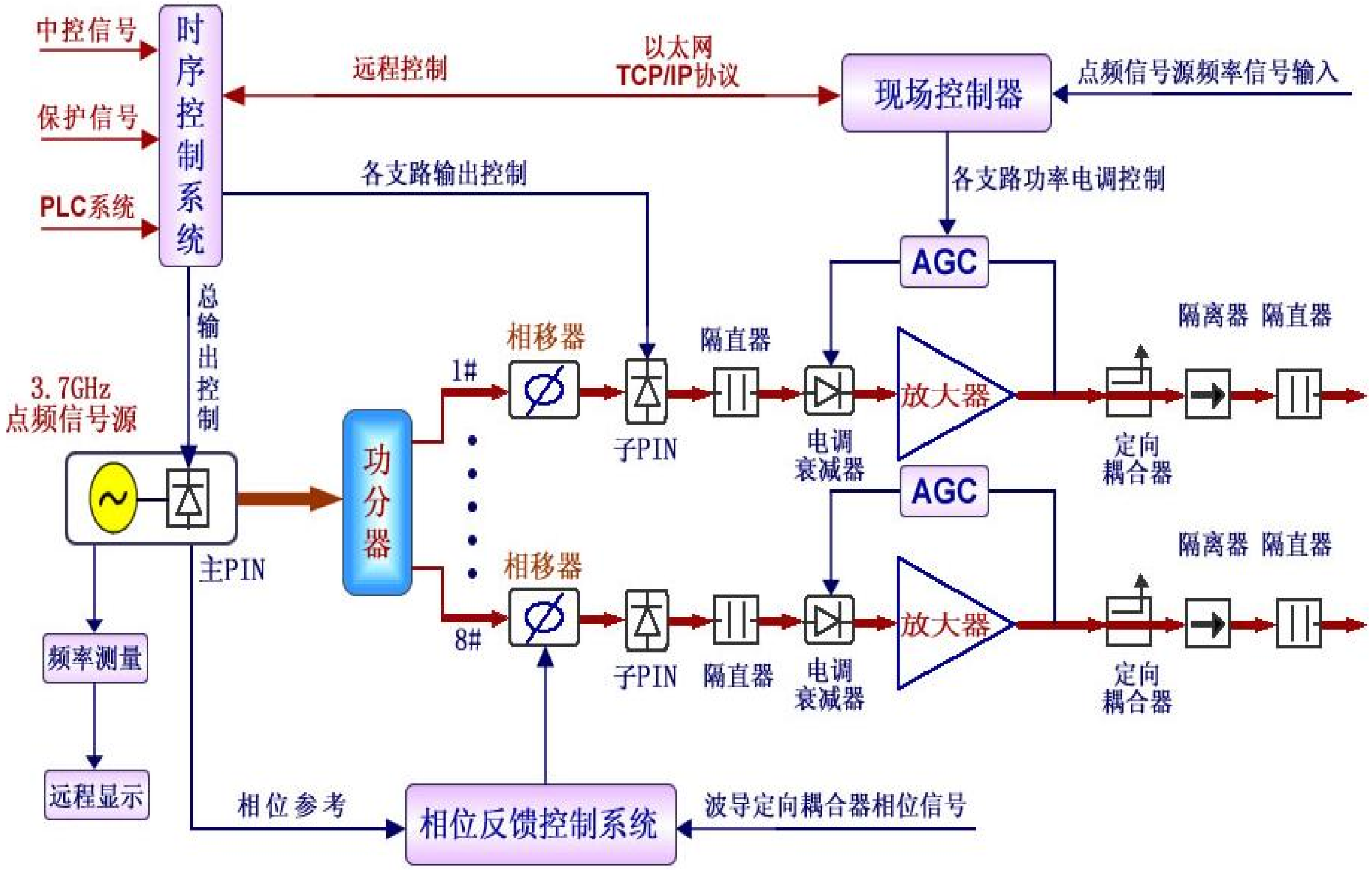
RF exciter

Function

- Provide RF power seed (~W) into the klystron
- Wave point frequency source
- Phase & power control (feedback or feedforward)

Composition

- Singal source (~μW)
- RF wave amplifier in two stage (μW~mW~W)



RF exciter of HL-3 LHCD system

High Voltage PS

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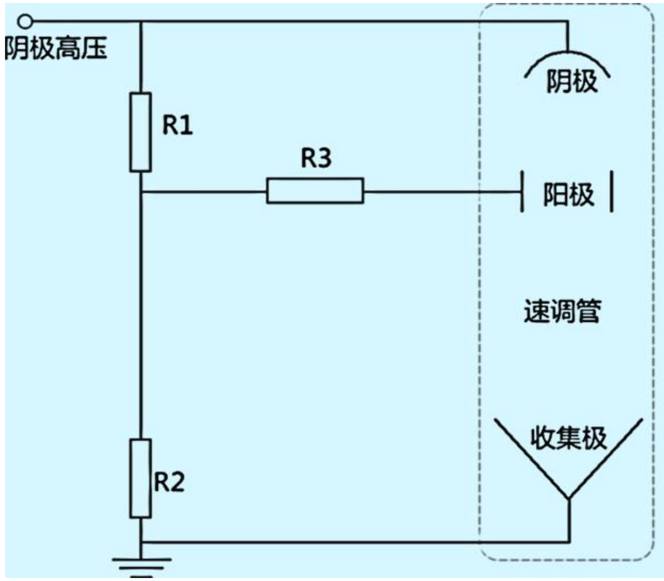
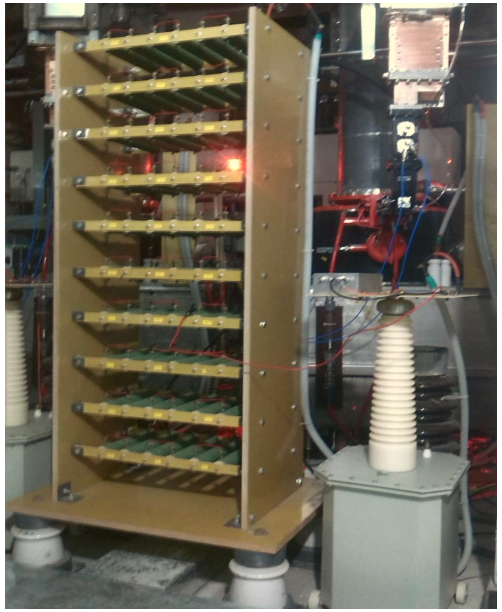
☐ Cathode PS

- Provide electrical power for klystron.
- Parameters: High voltage (~tens kV), Current (~tens A)
- Quickly shutdown in 10μs
- Pulse Step Modulation PS is developed

☐ Anode PS

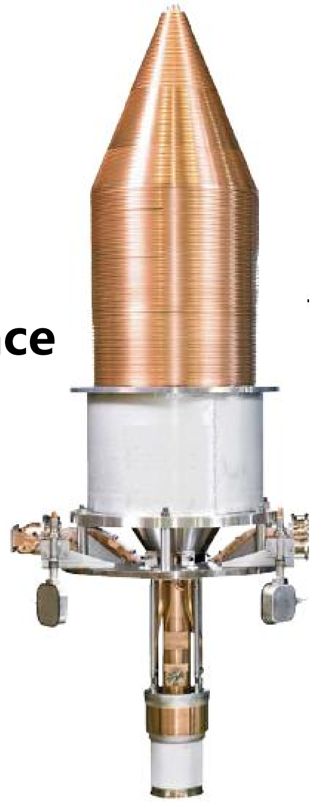
- Beam current control
- Operation status monitor
- Some klystron have no anode due to the stable operation realization

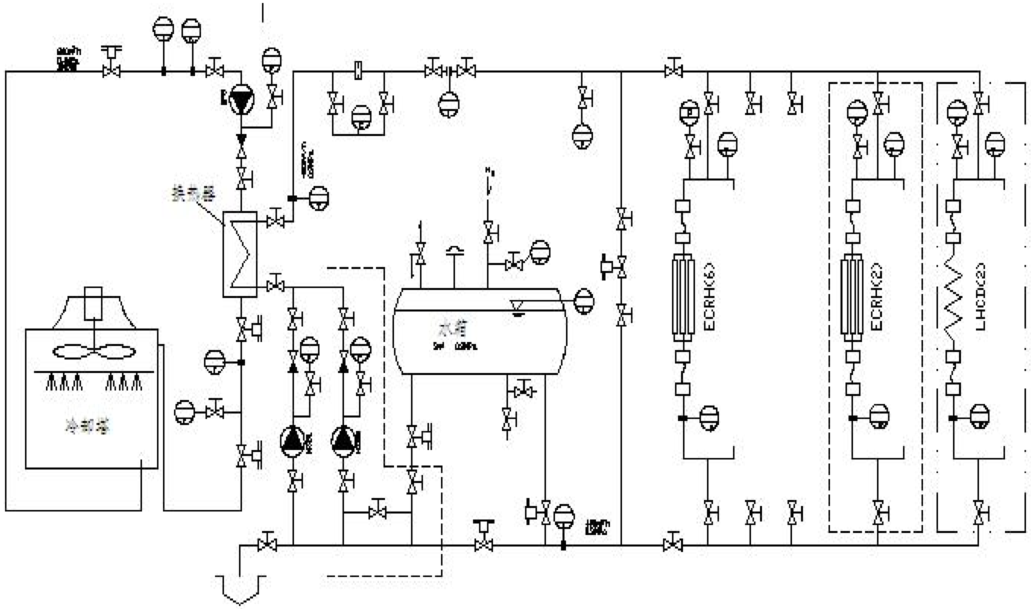




Water cooling system

- Cooling requirements
  - The efficiency of the klystron is ~50%
  - Power is transformed to the electron energy then deposited on the collector
  - Power loss at the resonant cavity
  - Magnet is made of copper with resistance heat in the long pulse operation
  - RF power loss at transmission components
  - RF power deposited at dummy load
  - RF power loss in the antenna
  - ......
- Water cooling system
  - High-purity deionized water
  - Closed circulating primary loop





Water cooling system of HL-3 RF system

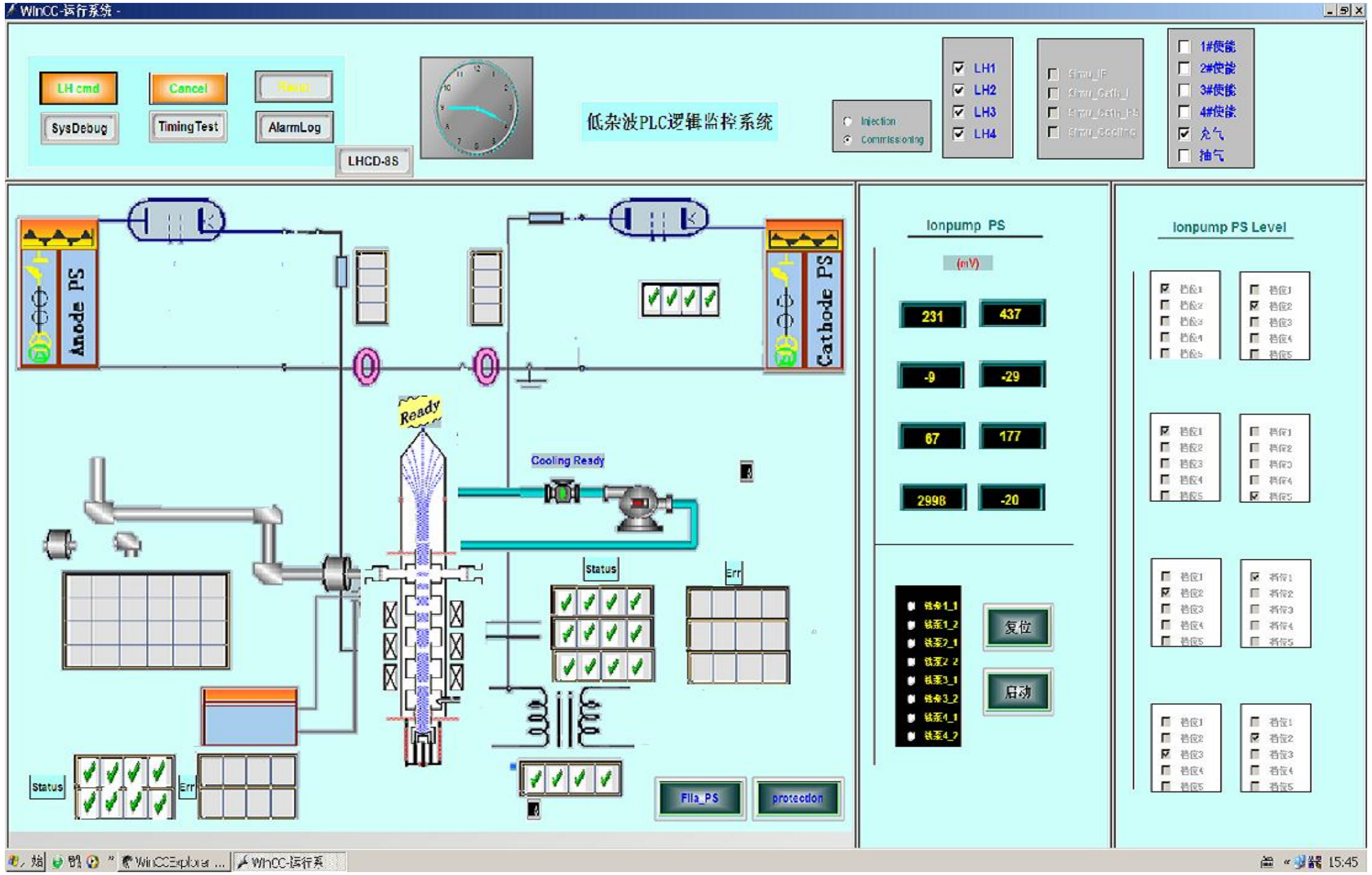
Control and Monitor system

☐ Operation conditions

- Operation status of the systems need to be monitored
- PLC is applied

☐ Composition

- Ethernet connecting the upper computer and equipment
- Node signal acquisition via F/V, V/F or optical fiber
- Control order or signal to the timing control system



PLC program running interface of HL-3 LHCD

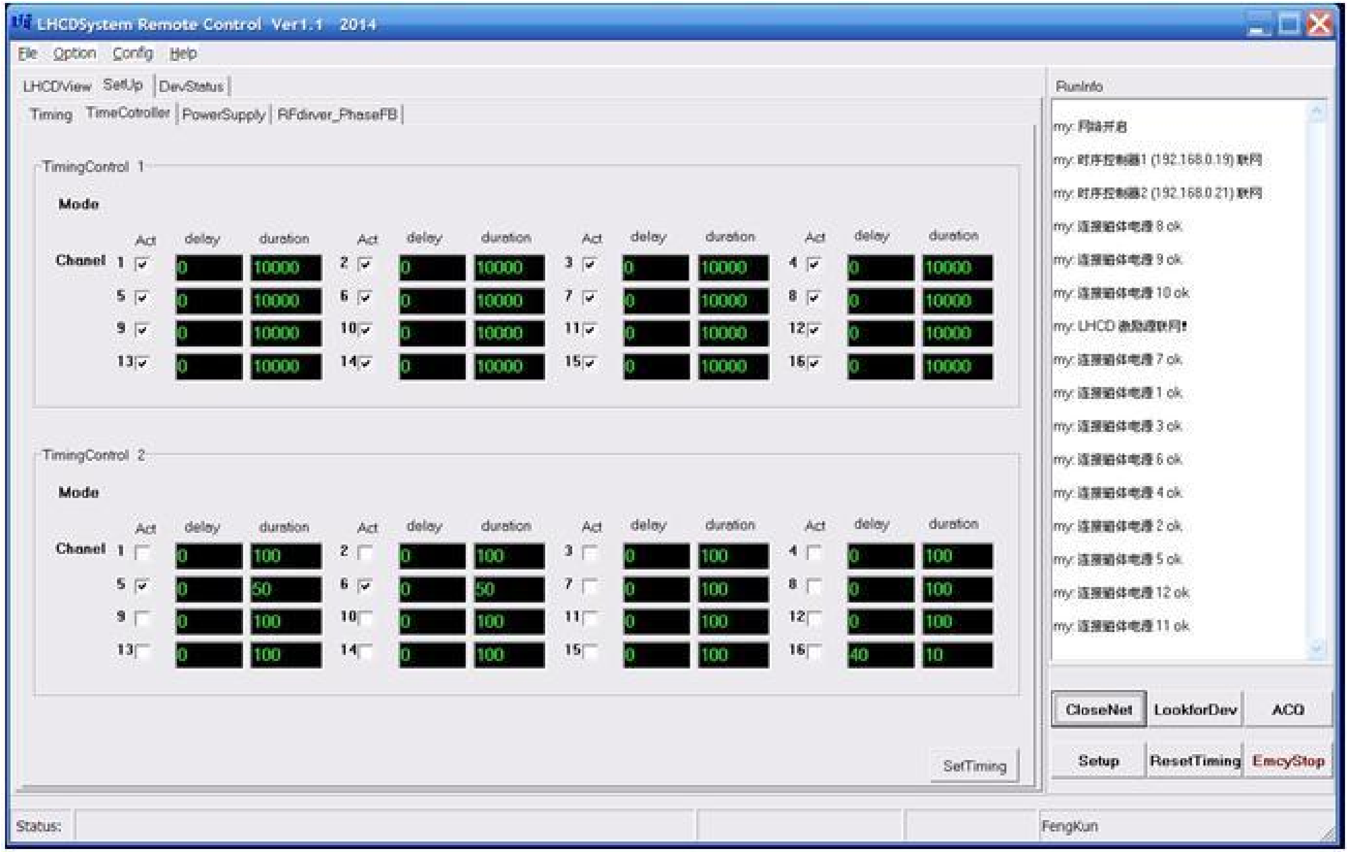
Control and Monitor system

Operation conditions

- System startup sequence is important for klystrons
- Timing control is needed

Composition

- Timing control equipment
- Receive the enable signal from center timing system and PLC
- Send down enable signal to start or stop the equipment (HVPS, RF exciter, acquisition ...)



Timing control interface of HL-3 LHCD

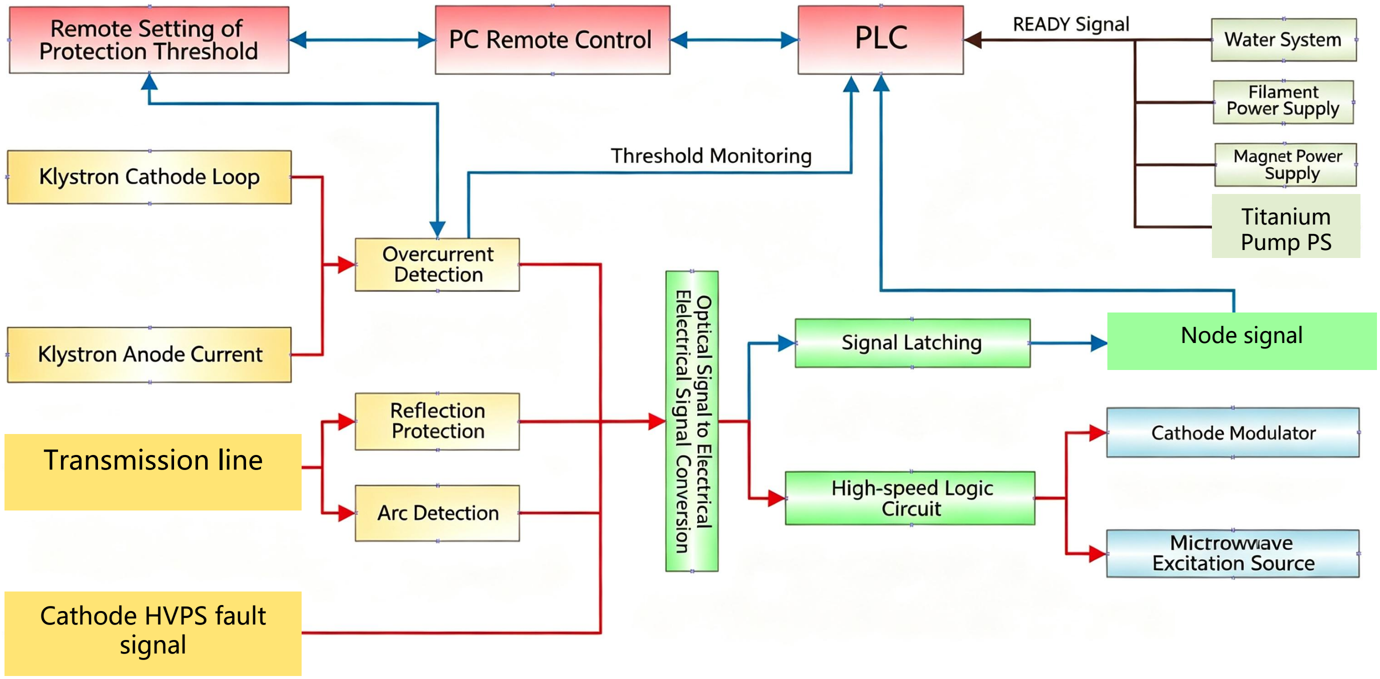
Protection system

Function

- Abnormal conditions response
- Shutdown the system in 10-20μs, directly catch original signal before acquisition
- Send fault signal to PLC system

Content

- Cathode overcurrent
- Anode overcurrent
- Arc in the WG
- High reflection power
- Titanium pump overcurrent
- RF exciter fault



Protection system of HL-3 LHCD

CONTENTS

General introduction

- **Function of transmission line**
  - To deliver the power from the wave source to the antenna
  - To measure the power and phase of LHW
  - To avoid klystron damage by the reflection power
  - To break the DC connection between the klystron and the device
- **Key technology**
  - Low power loss with long transmission line
  - Phase and power measurement
  - Reflection power control
  - High power capacity

Components——WG

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☐ Standard WG

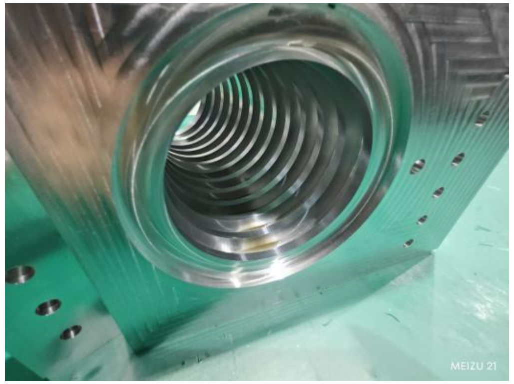
- WG components based on the WR series International Specification (BJ series in China). Such as WR187, WR229, WR284, WR430…
- Dominant Mode: TE_{10}

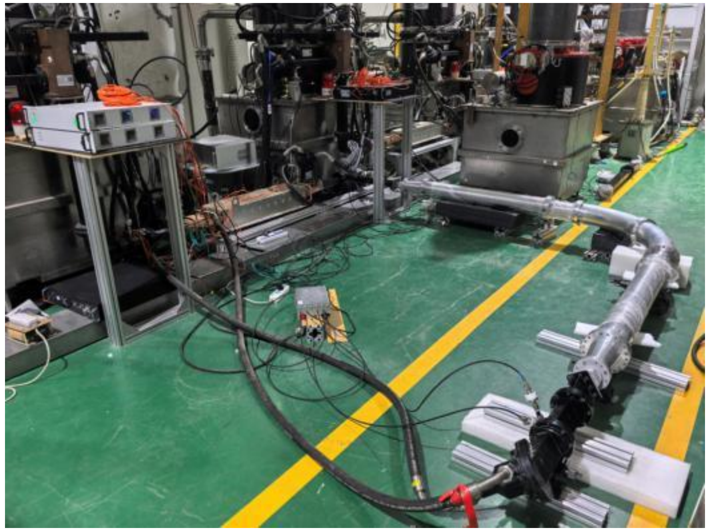
☐ Overmoded WG: Low loss

- Overmoded circular WG: TE_{01}
- Mode converter: TE_{11} (dominant mode in circular WG)~TE_{01} (Higher-order Mode)

Transmission line based on Standard WG (HL-3)

Transmission components of overmoded WG (HL-3)





Components——vacuum windows

□ Function

- To prevent the vacuum of the tokamak from the transmission line

□ Requirements

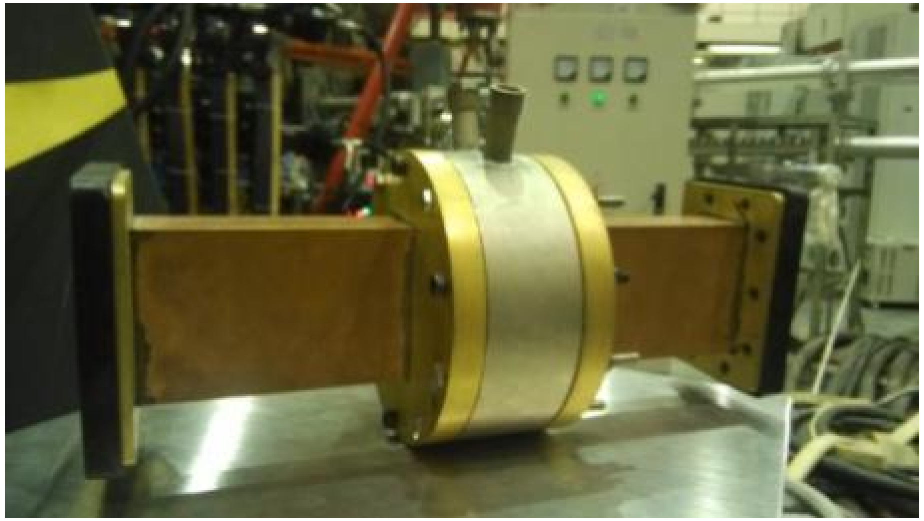
- High power capacity
- Low insertion loss and reflection
- Good thermal conductivity
- Reliable mechanical performance

□ Structure and material

- Pill-box ceramic window
- BeO: optimal choice

CA20320A BeO window developed by THALES, 250kW/CW

Sapphire window developed by SWIP, passed 200kW/1s power



Components——Isolator

Function

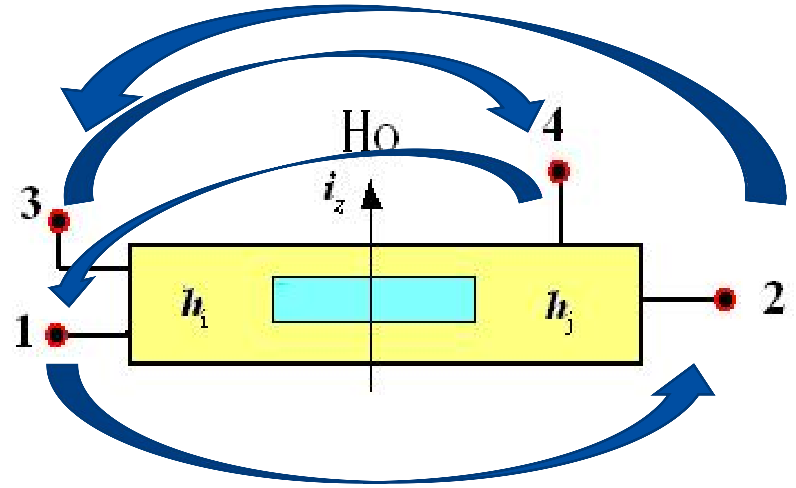
- To prevent the reflected power from returning to the original channel
- Ferrite used to achieve RF nonreciprocity

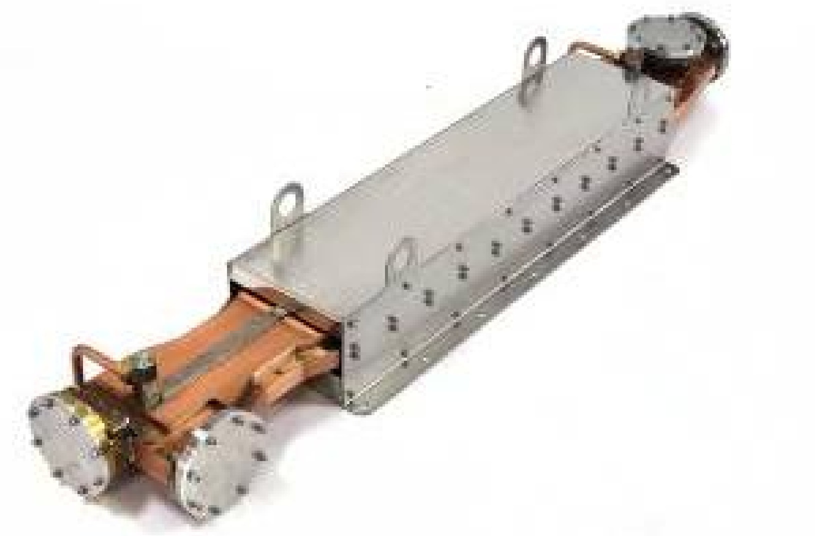
Structure

- Two 3-port circulators combined
- 1→2, 2→3, 3→4, 4→1, connecting water load to the port 3 and 4

Key point

- Temperature is very important, enough cooling





Components——DC break

Function

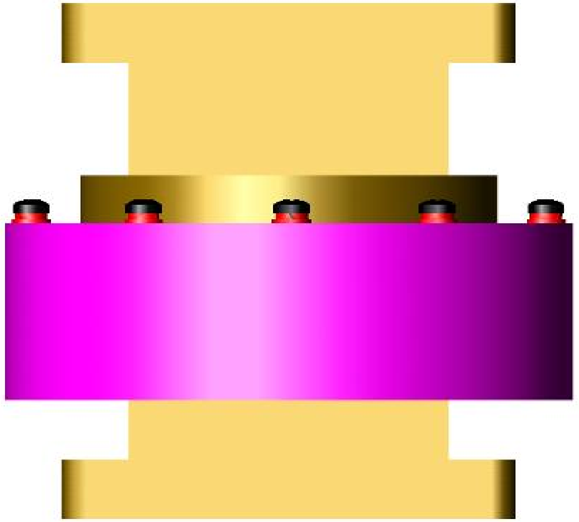
- To break the DC connection between the klystron and the tokamak
- Insulating capacity: ≥DC 3kV

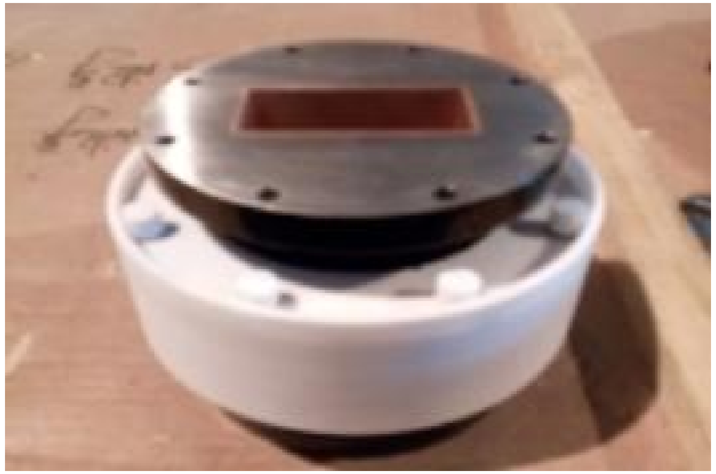
Structure

- Insulating gasket between WG choke flange and flat flange

Material

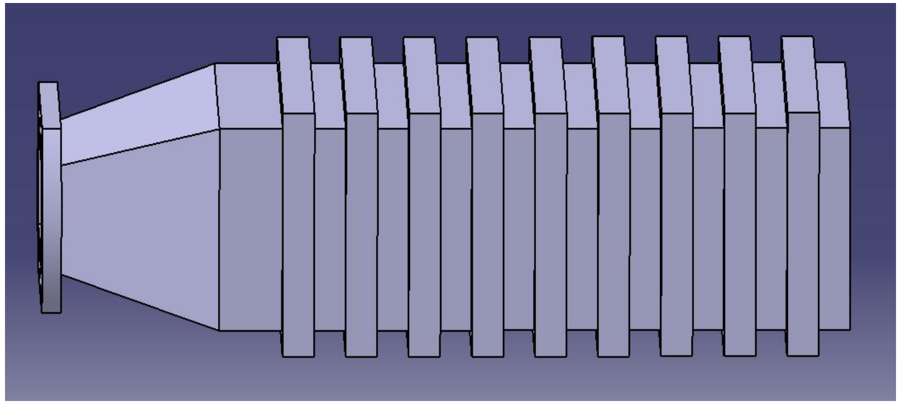
- Teflon is often used in the normal tokamak
- Ceramic could be the choice in D-T operation tokamak due to the nuclear safety requirement





Components——Water load

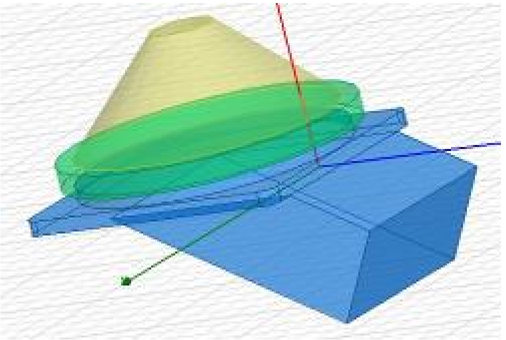
- Function
  - To absorb the reflected RF power
  - Capacity 250~500kW, even ~1MW (developing technology)
- Structure
  - Wedge-shaped BeO and water cavity
  - Flowing water takes the power away
- Key point
  - Bubble should be avoid in the cavity
  - Turbulent flow should be chosen
  - Fluid analysis is very necessary



Dry load

Water load

analysis and product



Components——power divider/combiner

- To make the transmission line simpler, the power can be combined from 2 channels to 1 channel at the klystron side
  - **Dua-window klystron transmits half power in one line**
  - **Compact structure needed nearby the klystron**
- To match the antenna input port, power from one klystron usually needs to be divided to 2-4 channels at the antenna side

RF test of 4-port power combiner

RF test of 4-port power divider

Components——directional coupler

Function

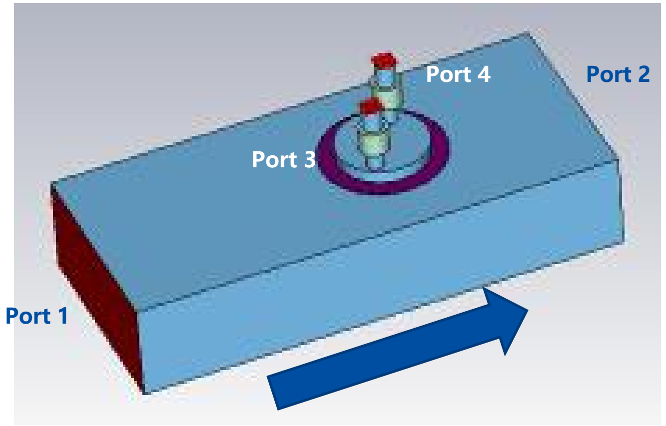
- To achieve sample RF signal of the high power travelling in the WG
- Coupling coefficient could be pre-calibrated by VNA

Structure

- RF signal coupled through single-aperture or Multi-aperture Coupling Array on the main WG
- The secondary WG is connected to the main WG covering the aperture

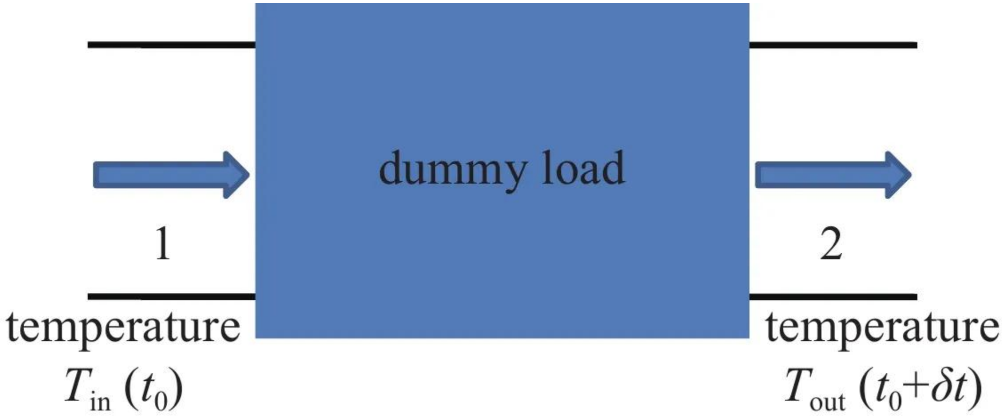
Key point

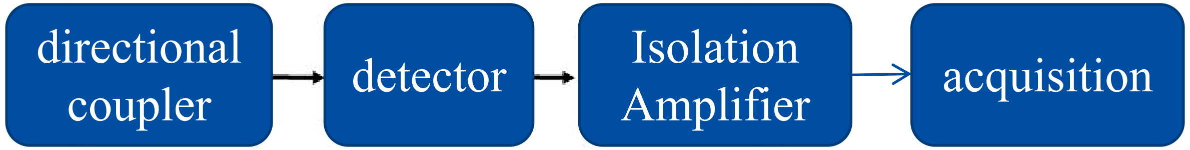
- The coupling coefficient shoud be designed to match the detector range
- The isolation is very important because the reflection coefficient is low



RF power measurement

- Calorimetric method
  - For long pulse and high power
  - Accuracy for long-term operation
  - Used for calibration
- Directional Coupler and detector
  - For short pulse and Lower power
  - Accuracy could be influenced, need calibration
  - Real-time monitoring capacity

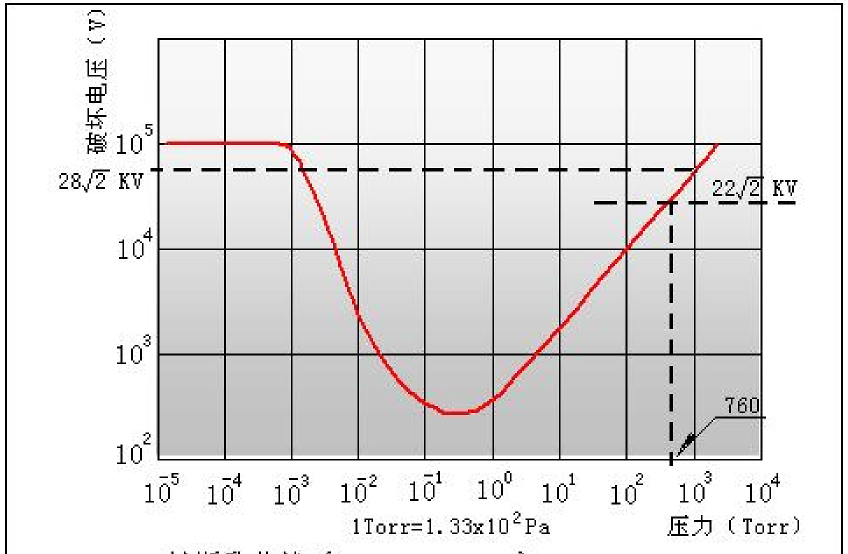




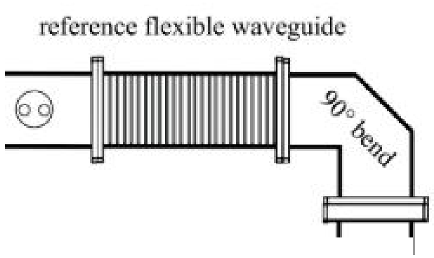
Multi-channel detector box and isolation amplifier

Components——function component

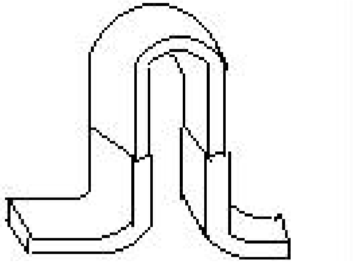
- **Evacuation & gas filling**
  - Paschen curve: 2 atm gas pressurized WG will increase the power capacity
  - Dry N_2 is the best choice
- **Arc detector WG**
  - Arc inside the WG may destory the components especially the windows and the klystron
  - Observation WG with a small window is needed to detect the light produced by arc
  - Usually faced to the ceramic window
- **Flexible WG and U-shape WGs**
  - Transmission line installation error makes it difficult to connect the last flange
    - ✓ Flexible WG is applied in part of LH system
    - ✓ Easily Arc inside and also easily break
  - U-shape WGs are applied in part of LH system
    - ✓ Not flexible enough but strong enough
    - ✓ Phase alignment function



帕斯欣曲线（Paschen Curve）



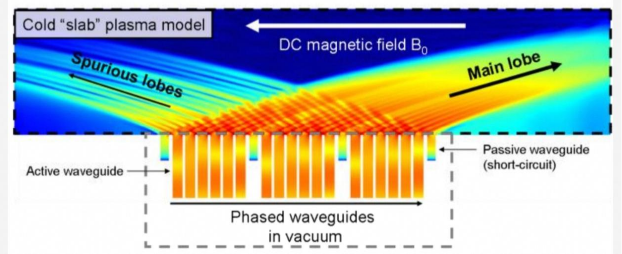
Straight flexible WG


U-shape WGs in E-field

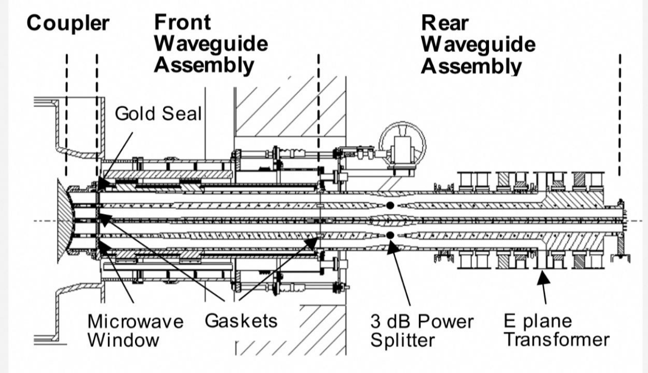
CONTENTS

General introduction

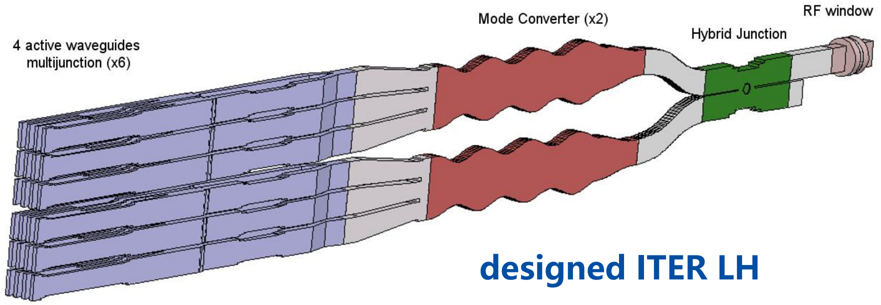
- Function
  - To launch LH power with certain spectrum
  - Low reflection coefficient
- development histroy(FAM\PAM\Grills)
  - 1970s: Individual WGs integrated together
  - 1980s-1990s: Multijunction grills antenna
  - 2000s- 2010s: PAM antenna
  - 2020s: HFS antenna, 3D print technology



launching spectrum of LH antenna



LH antenna of Alcator C-Mod module

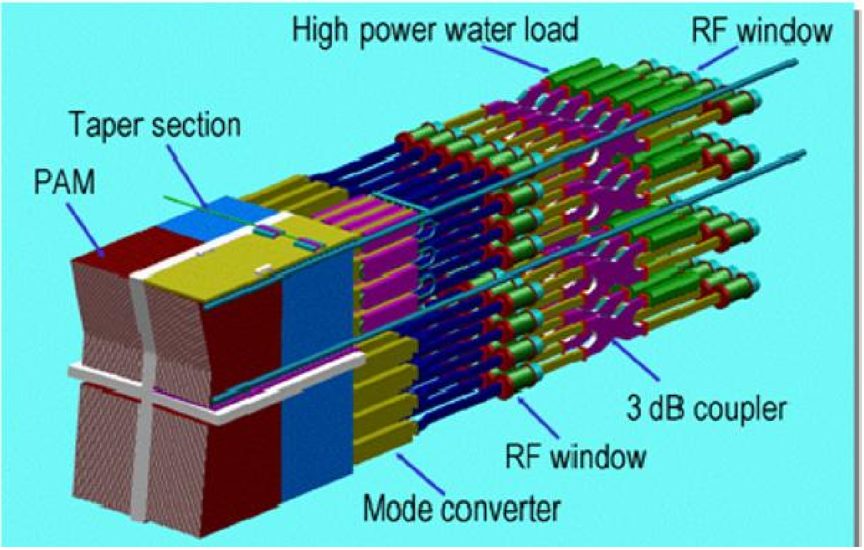


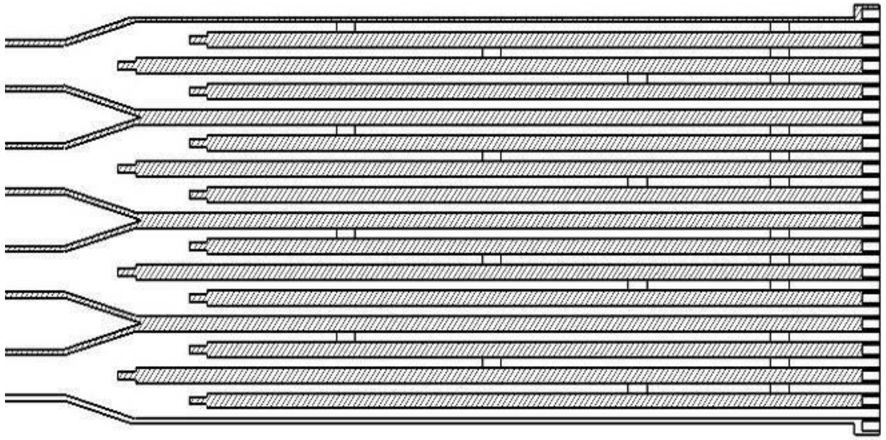
designed ITER LH antenna module

Structures

◻ Antenna body

- Main flange: connecting the antenna and the transmission line
- Taper section: shape changing to match the launching section
- Power divider section: to divide the power into different channels, transform the WGs to grills
- Phase shift section: to set the phase difference between adjacent grills certain value
- Launching section: to launch the power in a certain spectrum, need to be curved to match the magnetic field in front of the antenna

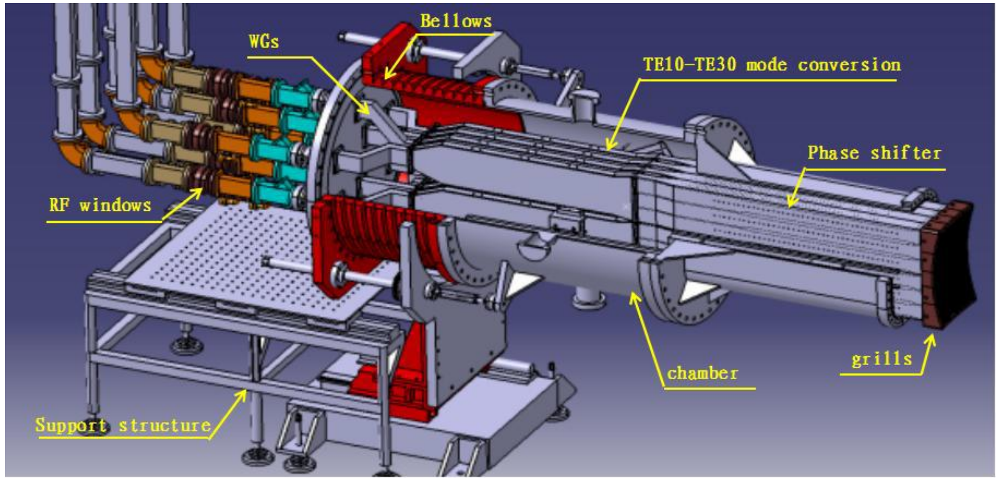


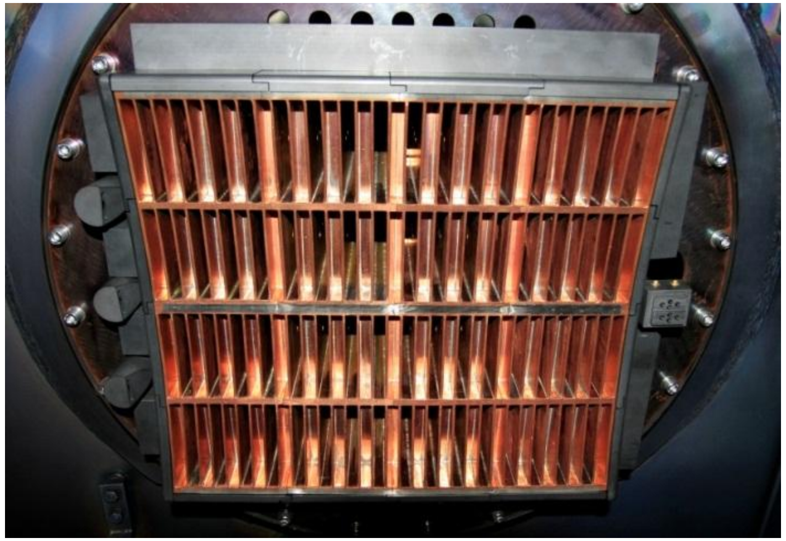


Structures

◻ Auxiliary system

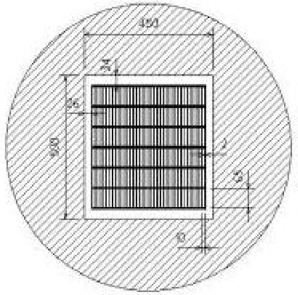
- Bellows & chamber: to keep the vacuum and the movable ability in radius direction
- Support structure: to support the antenna and the chambers, movable ability support
- Antenna limiter/ protection section: to provent the antenna mouth from the energetic electrons
- Gas puffing and diagnostic system





Antenna design

- **Antenna design is a balance work**
  - **The installation port of the machine should be confirmed, balancing the space and the power level**
  - **The space should be used as much as possible, so the grill distribution design could start first, balancing the WG form, grill size and port size**
  - **Then the spectrum could be designed, balancing the plasma parameters, directivity, main lobe position and the port size**
  - **The phase shift section should be optimized, balancing the length limit and the stage size**
  - **The antenna mouth should be curved to match the magnetic field, balancing the different plasma configurations**



[illegible]	33-6	[illegible]	33-6
[illegible]	11-60	[illegible]	10-60
[illegible]	2	[illegible]	2
[illegible]	6	[illegible]	6
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[illegible]	9.5	[illegible]	26
[illegible]	49	[illegible]	49

[illegible]	33-6	[illegible]	33-6
[illegible]	10-65	[illegible]	11-74
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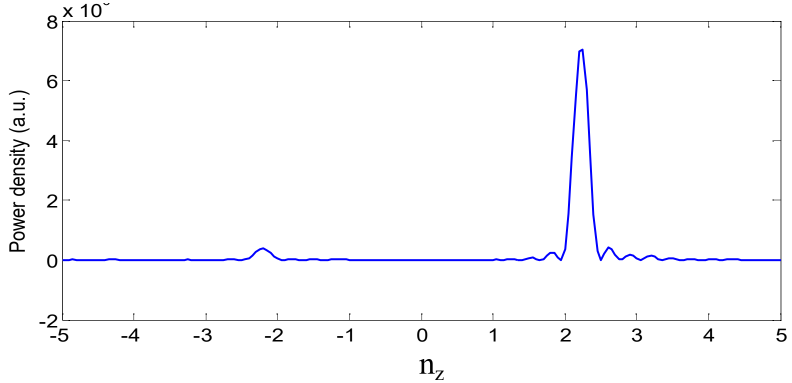
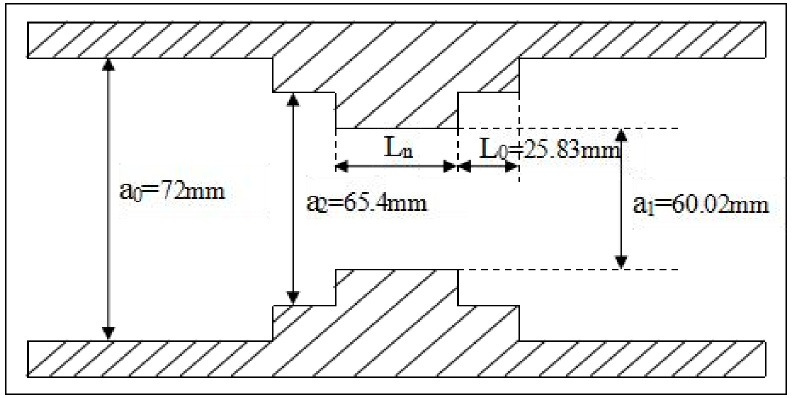




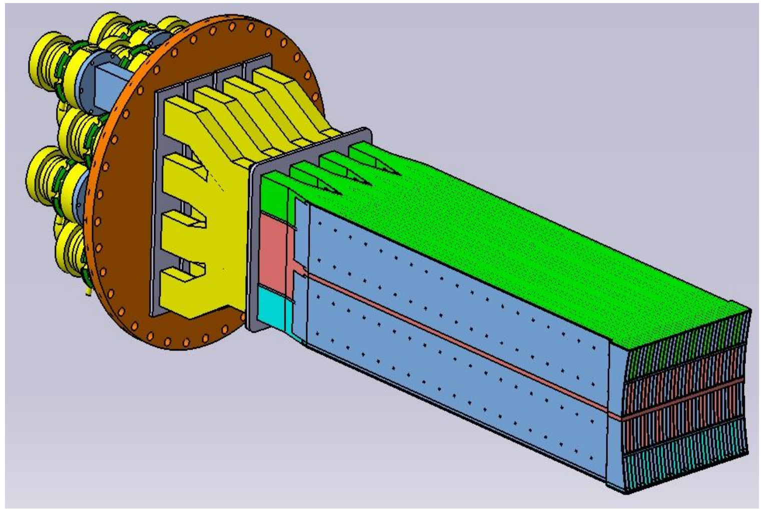
Forming

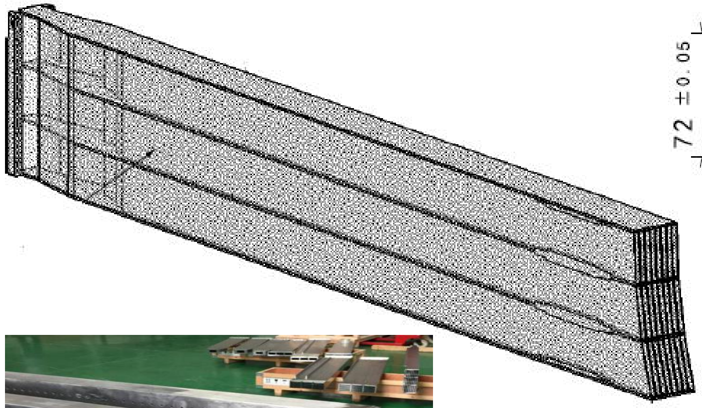
Assembly form

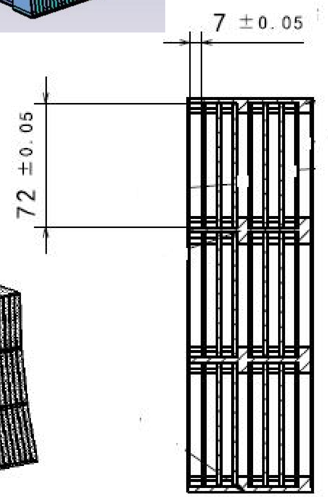
- An unit contains the grills from the same WG channel or same column
- Different units are assembled in certain order

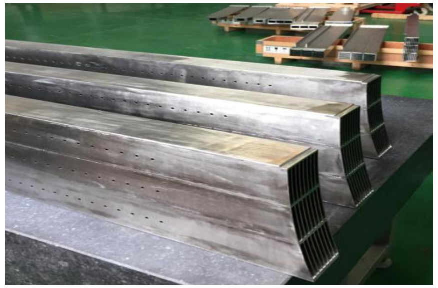
Forming process

- The grills are combined by vacuum brazing from plates of material
- The units with different function are assembled first
- The antenna body are assembled in toroidal direction in the last process
- Brazing is the most important process









Test of RF parameters

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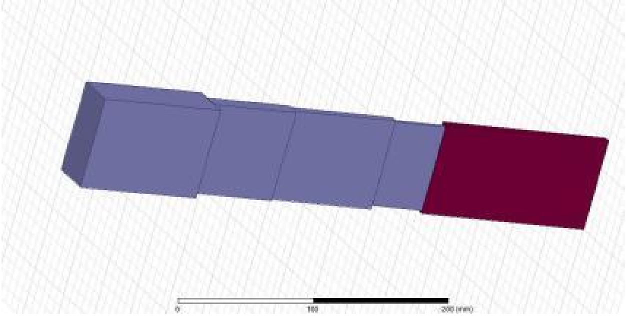
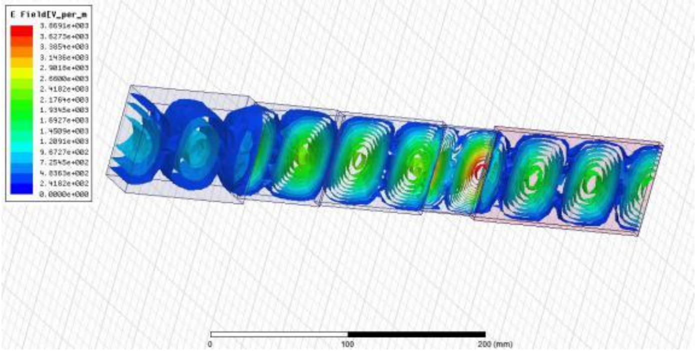
- ☐ **Every antenna is designed specially for a certain purpose, non-standard product**
- **The measurement of the antenna follows the same way: to develop a special test component and then measure the parameters by VNA**
- ☐ **Test component design**
- **The component should be put into a grill**
- **Grills should be considered in the design**
- **Match loads that could be put into the grills are necessary**



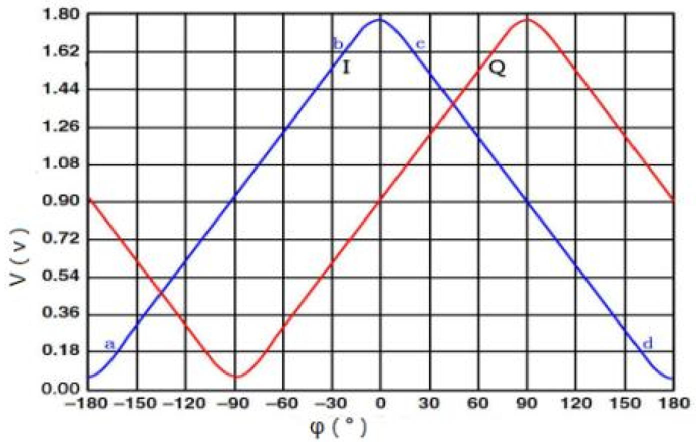


Installation & Commissioning

- The antenna system with large size is difficult for installation due to the limited space around the tokamak
  - Lifting tools are developed to solve this problem
- The high power components and equipment need commissioning
  - Transmission components and the klystron could be commissioned offline
  - The antenna is always commissioned online，coupling optimization experiment at the same time

Phase control

- □ **Phase feedback control**
  - Phase difference between the transmission lines influents the spectrum
  - Feedback control makes the spectrum stable
  - Phase difference could be seted every shot
- □ **Phase detective unit**
  - Signal from directional coupler
  - Based on phase from one klystron
- □ **Phase control unit**
  - Fast response time is needed
  - Information achieve and settle down
- □ **Phase shift unit**
  - In the RF exciter



CONTENTS

Summary

- LHCD system was built on many tokamaks
- LHCD technology developed much these years
- Face to the fusion reactor，LHCD needs to solve problems
- PDI decrease the power deposition in high parameter plasma
- Advanced antenna for fusion reactor

Thank you！