Science Island

中国科学院 合肥物质科学研究院 等离子体物理研究所

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IC Principles: Technology Overview

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ITER International School, July 20-24,2026

Chengdu, China

The ICRF System

Heating via Ion Cyclotron Range of Frequency (ICRF) waves has reactor-relevant features

- **No density limit** to couple power to high density plasmas, increasing absorption efficiency with β_i
- **Direct ion heating** possible in D-T plasmas
- **Impurity control** by heating the centre
- **Technology available for continuous operation**
- **High efficiency and Modest price ($/MW), commercially available sources**

Flexible Heating System

- **Existing technology spans frequency range for high-field concepts ~ 120 MHz @ 12 T**
- **Heating / current drive (k// spectrum)**
- **Various heating schemes**
  - ✓ Minority heating
  - ✓ 2nd harmonic heating / higher harmonic heating
  - ✓ Synergy with NBI
  - ✓ etc..

The ICRF System

Any ICRF System can be divided into the following main areas:

(1) Power evolution between the generator and the antenna: RF power→ be properly transferred to antenna

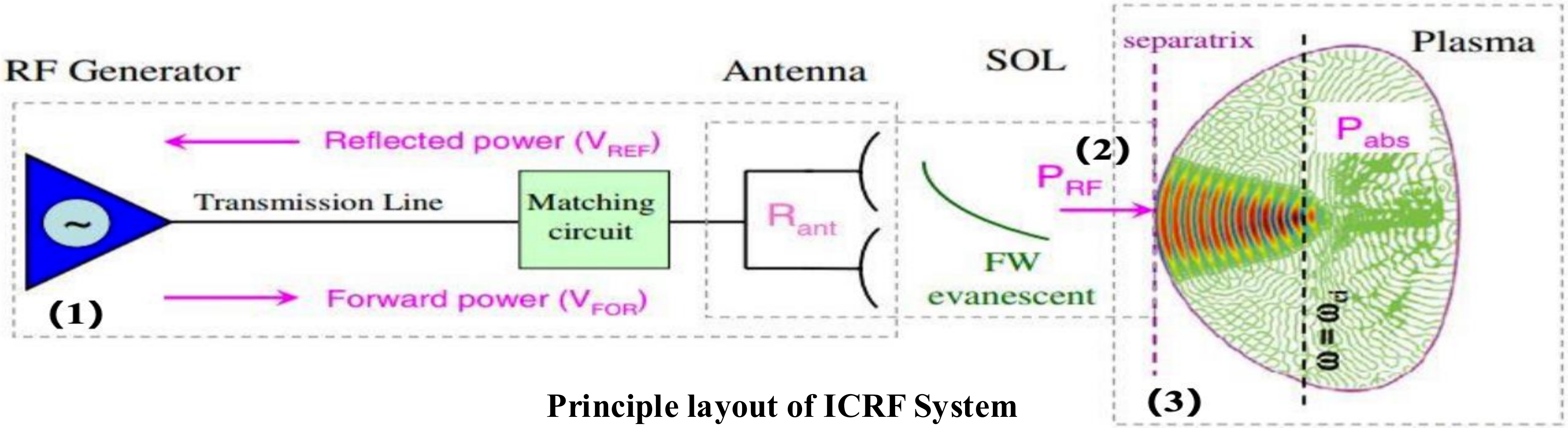
- **Depends on the antenna and on the layout of the impedance matching circuit**

(2) Power coupled from the antenna to the plasma: The power →be efficiently coupled to the plasma

- Depends on **the antenna** but is particularly sensitive to the characteristics of **the plasma in SOL**

(3) Power absorption inside the plasma: The coupled RF power →be efficiently absorbed in the plasma

- Depends on **the antenna** but also on the **plasma core parameters** and on **the equilibrium** magnetic field



Principle layout of ICRF System

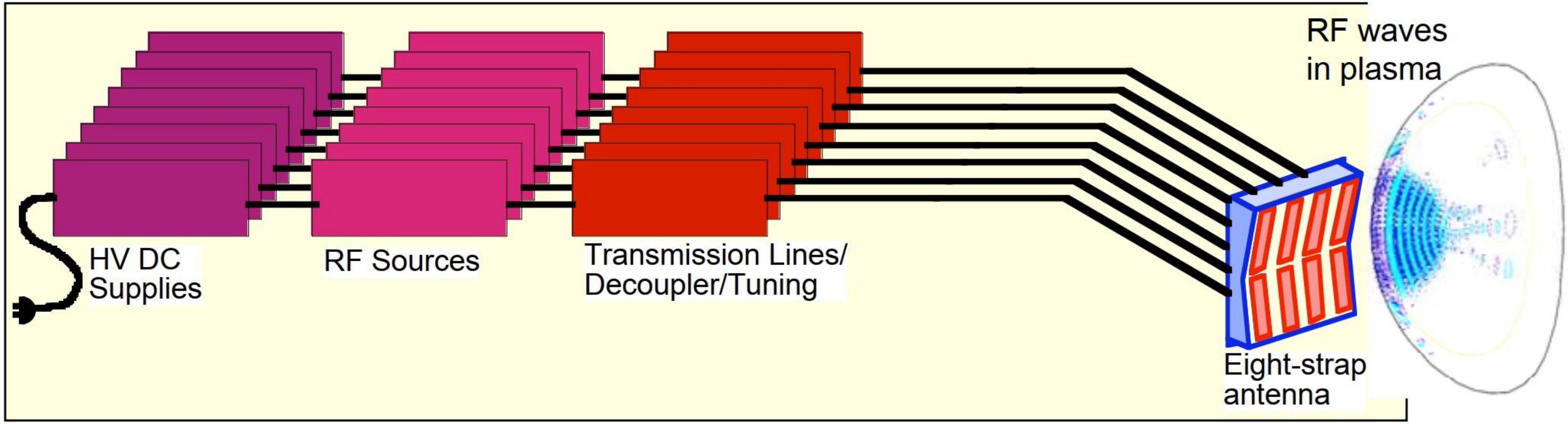
Contents

ICRF System Components

An RF system is composed of:

- AC/DC power supply system
- DC/RF converters system
- Transmission line system
- Antenna system + Auxiliary system interfaced with Tokamak

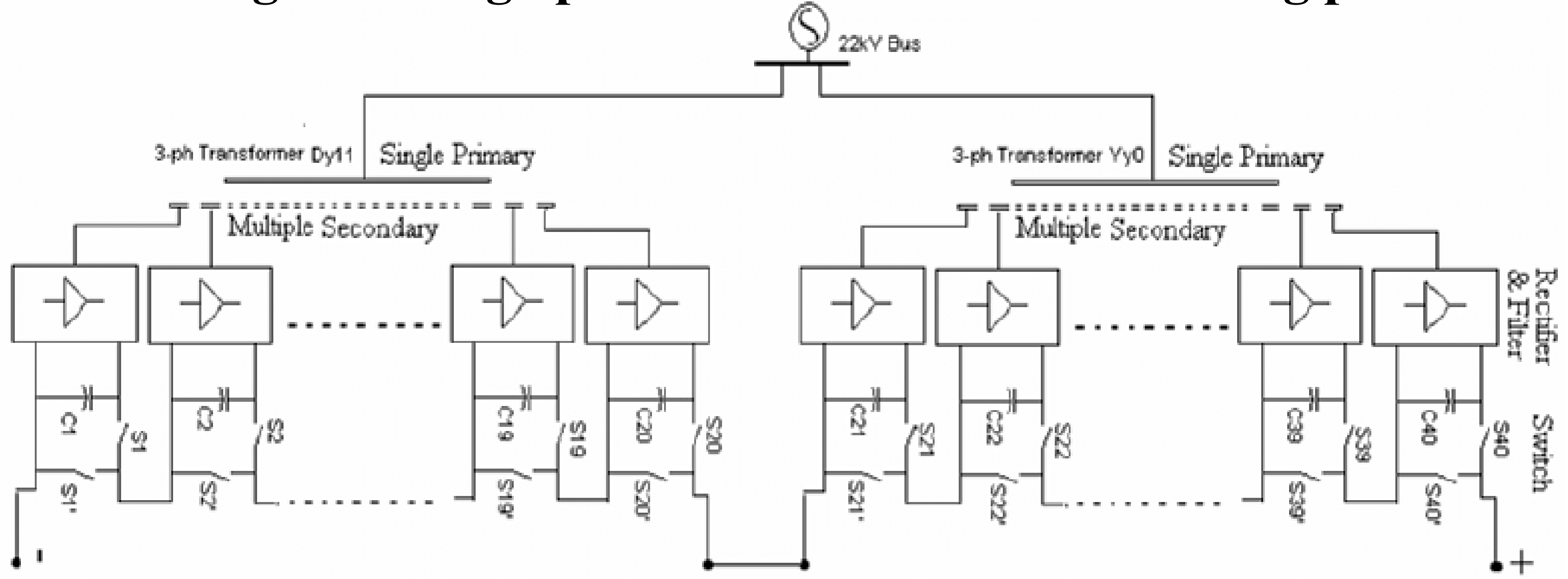
Type of component vs. System	ICRH
Frequency range	25 to 120 MHz
DC Voltage level	10-30 kV
RF Tube	Tetrode
Transmission line	Rigid Coaxial
Antenna/Launcher	Radiating loops



High Voltage Power Supply: AC/DC

- **The energy is taken from the 50 Hz grid at 22 kV level from onsite substations**
  - Each HVPS supplies RF source: 1 driver stage & 1 end stage.
  - Dry type multi-secondary transformers and Pulse Width Modulation rectifiers.
  - Modular solution provides HVDC output with precise control, low ripple, fast dynamic response and minimal stored energy.
  - **Dynamic adjustment of anode voltage allowing optimization of RF tubes working point**

Large use of PSM techniques:
- Fast switching for protection in case of arcs
- regulation for stable operation



RF Source: Converting from DC to RF

Two major competing RF Power Technologies for use in ICRF System:

- **Vacuum Electron Devices (VEDs)**
  - Tetrode based
  - Dircode based

Tetrodes

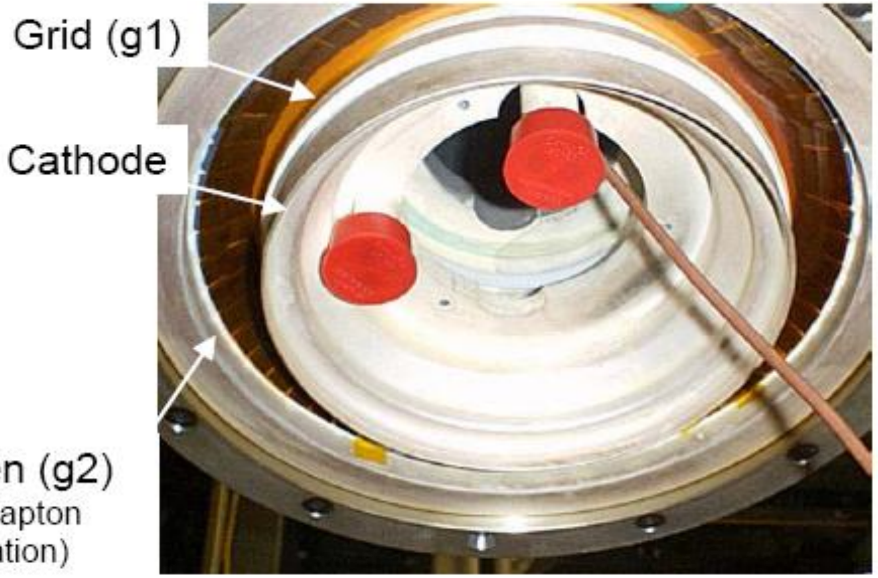
- **Solid State Amplifiers**
  - Large number of connectors results in more possible failure points
  - Increases mechanical design complexity
  - High losses compared to VEDs
  - Under development for DTT and SPARC

Kathleen Quinlan, DTI 2024

EIMAC-4CM2500 Power Tetrode

Top view

Bottom view



Maximum ratings:

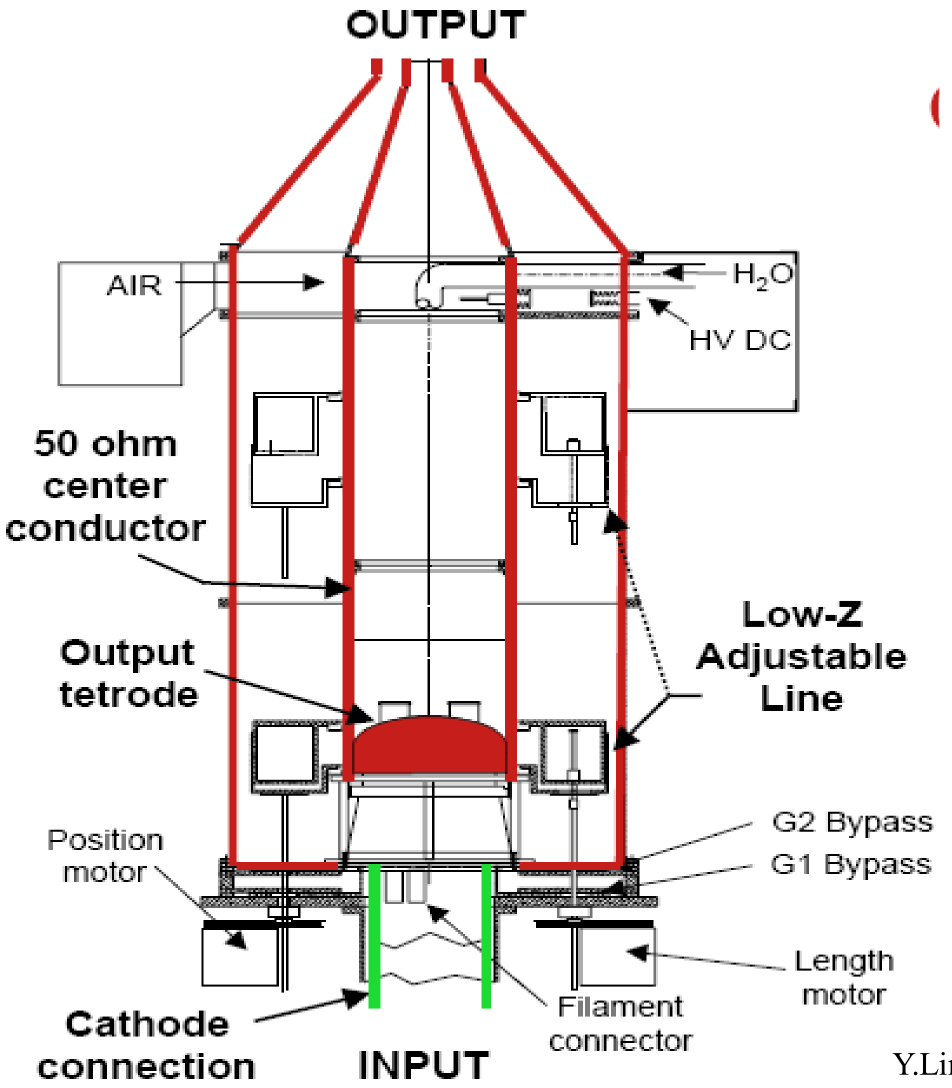
Anode voltage	27 kV
Screen grid voltage	2500 V DC
Control grid voltage	- 1000 V DC
Anode direct current	190 A
Peak cathode current	800 A
Screen dissipation	20 kW
Grid dissipation	8 kW
Anode dissipation	2.5 MW

Characteristics:

Type of cathode	Thoriated tungsten
Heating	Direct DC
Filament voltage	15.5 V
Filament current	640 A
Max surge current	1500 A
Operating position	vertical, heater terminals down

RF Cavity

- Tetrode tube fits in base of cylindrical cavity.
- Low impedance line transformation to match tube impedance to 50 ohm output line.
- The low impedance line is movable and expandable to provide matching over entire frequency range.
- Cavity components are forced air cooled.
- Anode cooling will be fed through center conductor.



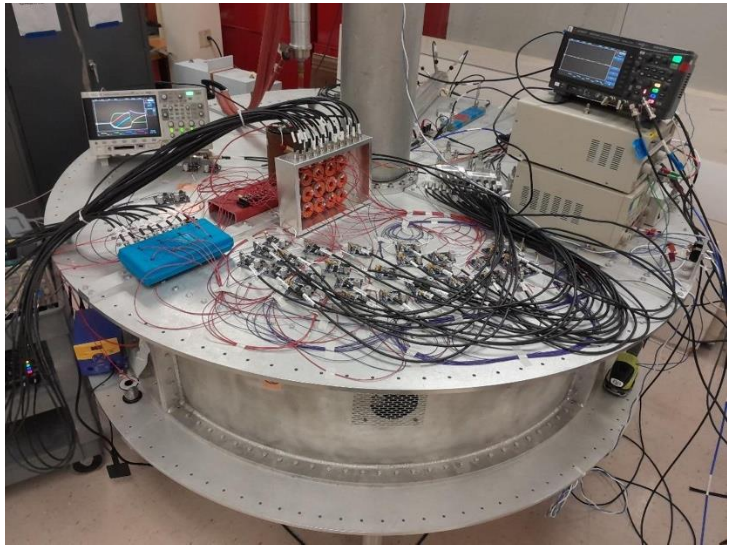
Y.Lin 2008 Summer school

Solid-State ICRH transmitters at SPARC

- **Transistors Mounted On Cavity Endplates**
  - ✓ Commercial transistor drains are coupled directly to the cavity
  - ✓ Magnetic coupling loops extend axially into cylindrical cavity
- **Cavity tuning & output control is done at once**
  - ✓ The cavity output is a coaxial transmission
  - ✓ which then connects to two central axial tuning slugs, not by tuning individual transistors

Proof-of-Concept: 120 MHz, 42.7 **kW (32 modules) and 75% efficiency achieved**

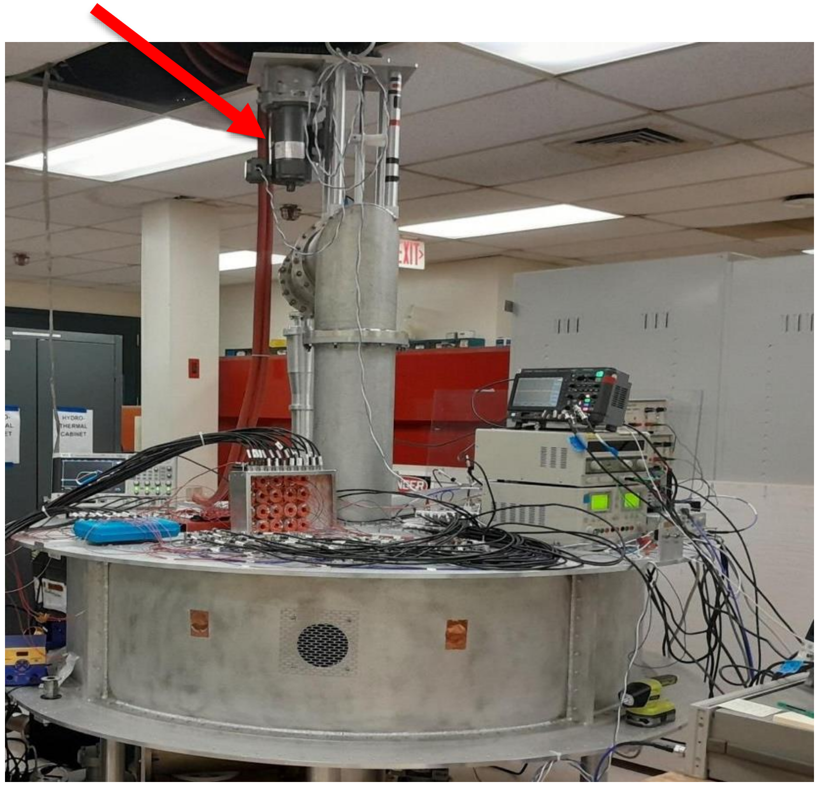
Kathleen Quinlan, DTI 2024



Transistor module placement in one segment of combiner top plate

Internal view cavity showing coupling loops and transmission line

Top central axial tuning slug and motor



Dr. Marcel 2023 IEEE Pulsed Power Conference

Solid-State ICRH transmitters at SPARC

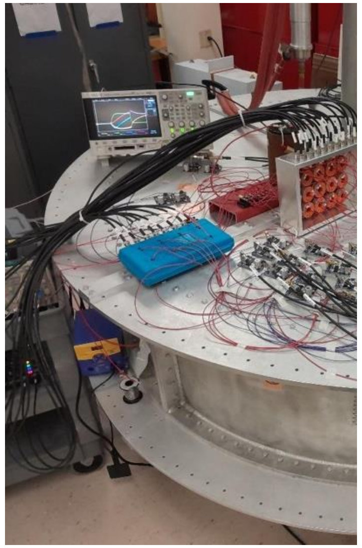
- T ... 32 ... l
- C ...

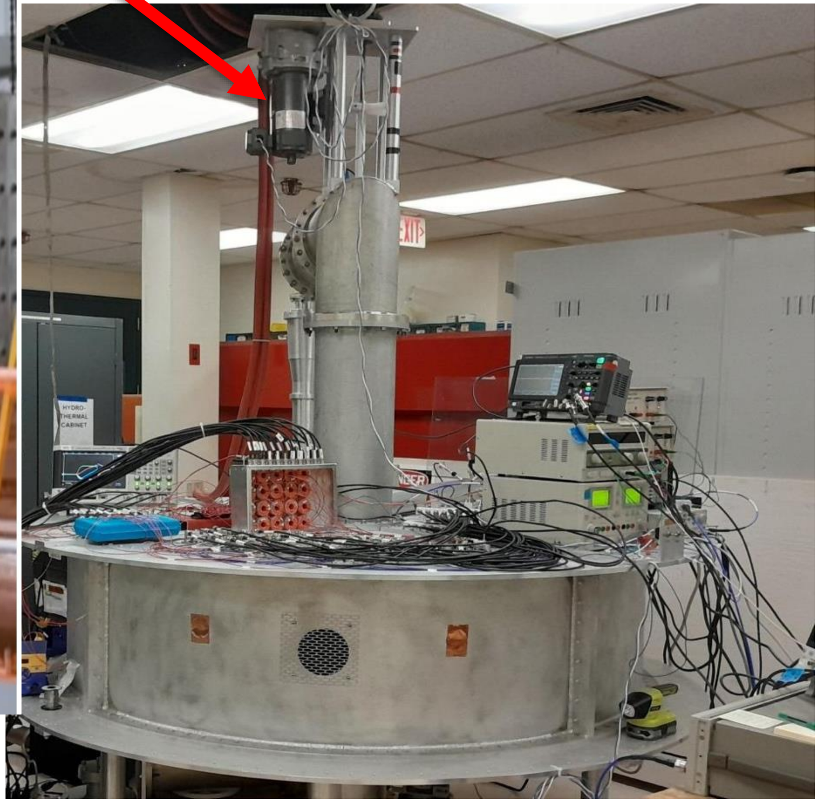
- Some information can be obtained from YouTube, as shown in the picture below.
- Some transmitters and some transmission systems have already been installed.

✓ The cavity ...

✓ which then ... individual t...

Top central axial tuning slug and motor

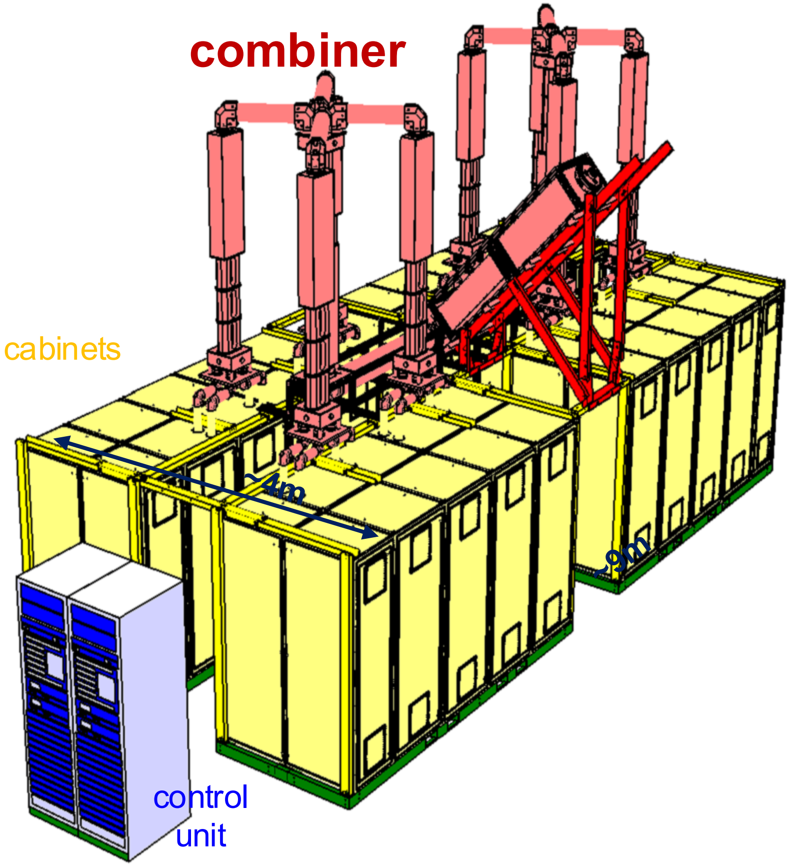




Transistor module placement in one segment of combiner top plate

Internal view cavity showing coupling loops and transmission line

Solid-State ICRH transmitters at DTT



ENEA is procuring two solid-state broadband ICRH transmitters, first in the world, to be used in DTT.

They consist in **128 RF modules of 11 kW**, adapted from a reliable design, routinely used in broadcast transmitters.

They will deliver an output **power of 1.2 MW** for 50 s in the frequency **range 60-90 MHz**, using more than **1500** transistors and 600 plug-in power supplies with a wall-plug efficiency larger than **52%**.

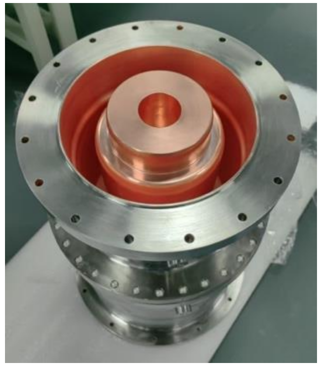
S. Ceccuzzi FED2025
S. Ceccuzzi IEEE 2025

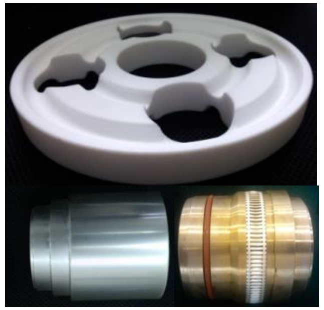
- **On the contrary, multistage combination schemes consist of classical multiport components, such as Wilkinson and Gysel combiners, 3-dB hybrid couplers, and impedance transformers, which can be designed with a broadband response.**

Transmission lines

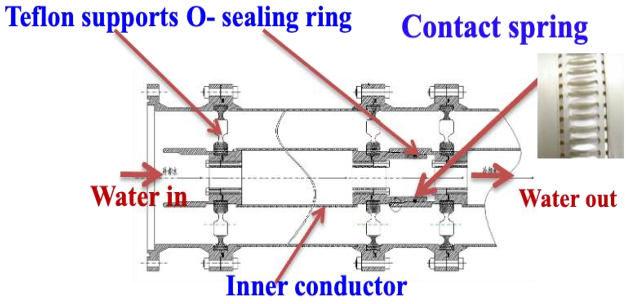
The two main elements of a transmission line are the following:

- **the vacuum windows as the interface with the antenna**
  - To ensure the vacuum integrity of the torus, to have **good mechanical** qualities and obviously **good RF** properties
  - **Power handling** capability: 1 to 2 MW for long duration time.
  - Special attention has to be devoted to **the shape and the design of the ceramic windows** in order to withstand the required large voltage.
  - To day, currents up to 1 kA and voltages up to 50 kV have been achieved.
- **Pressurized transmission lines are made of large diameter coaxial transmission lines in order to withstand the large RF voltages**
  - Active cooling needed (High power CW operation)



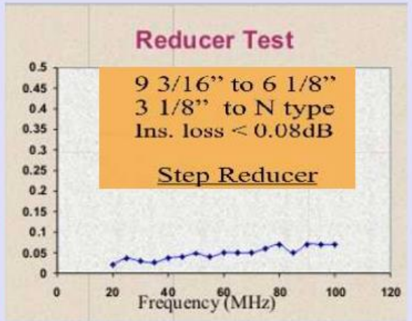


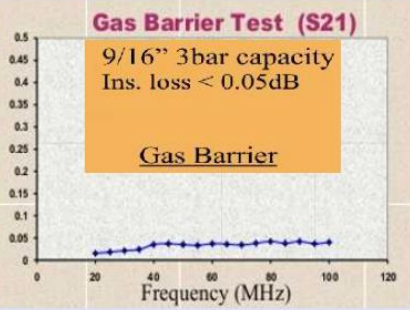
Joint and Teflon support

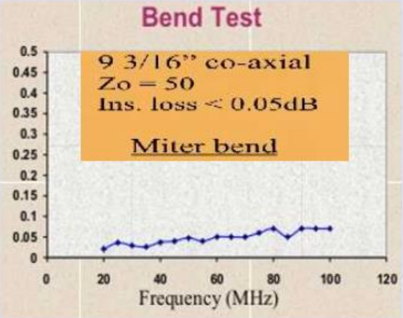


Coaxial line structure

Example of Transmission lines







S.V. Kulkarni IIS 2012

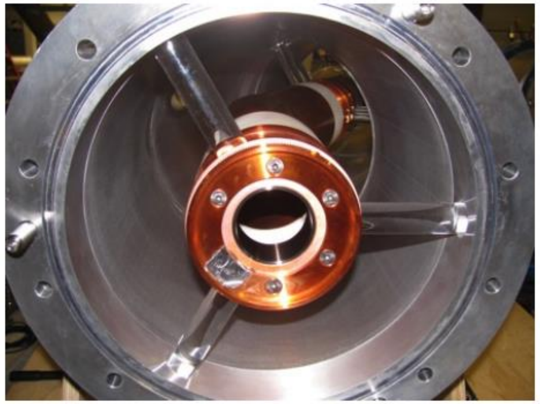


Fig. 19. SRA transmission line sections.

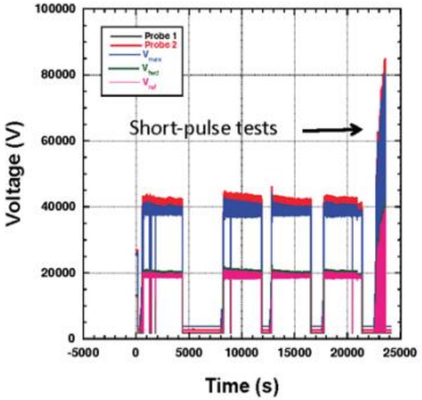


Fig. 20. Voltage vs. time for four 3600s pulses, followed by 0.1s pulses at voltages up to ~ 85 kV.

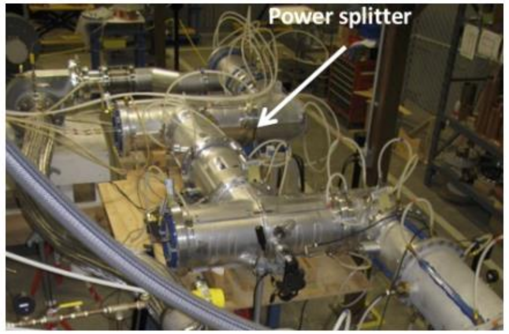


Fig. 21. 6 MW power splitter.

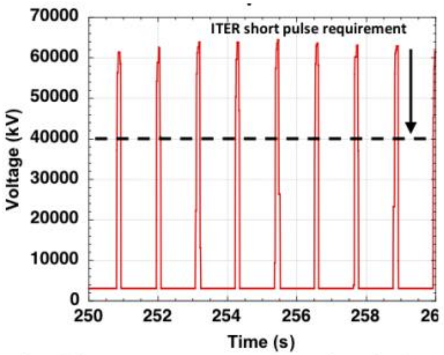


Fig. 22. Voltage vs. time for 0.1 s pulses.

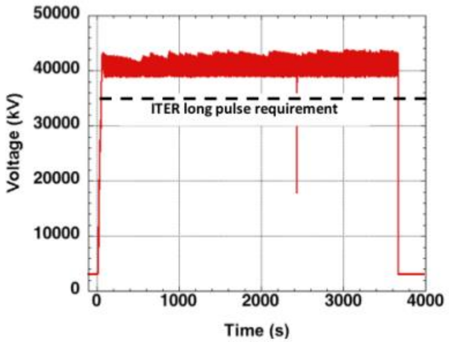


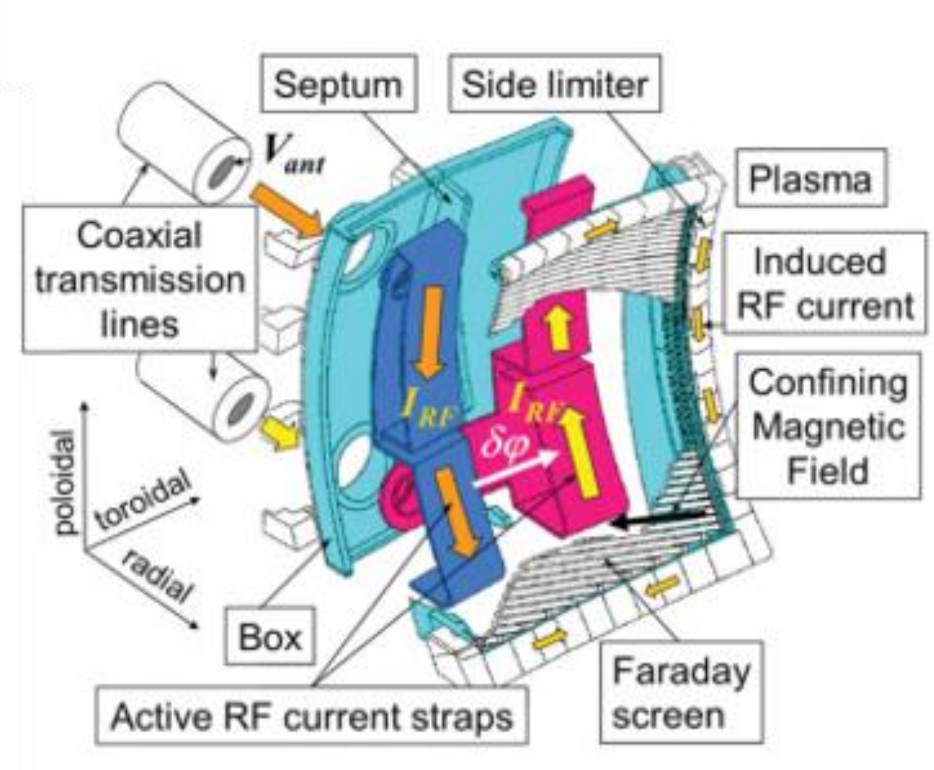
Fig. 23. Voltage vs. time for 3600 s pulse.

W. Helou, CWRF2022

ICRH Antennas

- An ICRH antenna integrates electromagnetic, vacuum, mechanical, and protection functions

Current straps	Excite fast magnetosonic waves; Array-current Amplitudes and Phases set the spectrum
Antenna box	RF return conductor and structural support
Faraday screen	Suppress electric field parallel to the static magnetic field
Vacuum TL	Bring RF through vacuum and withstand roughly 40–50 kV at high VSWR



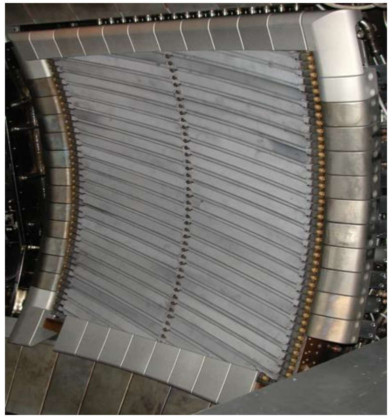
Shared objective: sustain plasma coupling within allowable Vmax, Emax, and RF-loss limits

Colas L, Nucl Fusion 2022

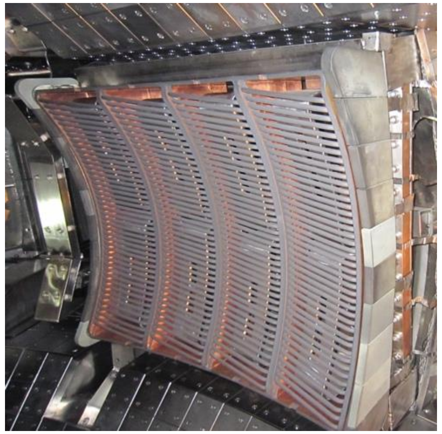
ICRH Antennas

ICRH antenna typically consist of multiple-straps, located in tokamak ports

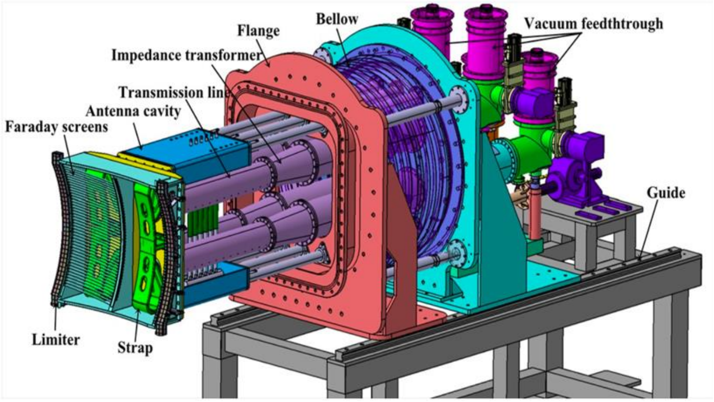
- **To date they are made from inductive loop antennae carrying poloidal RF current.**
- **A Faraday shield is required to impose wave polarization, to avoid parasitic loading into other wave modes and prevent direct streaming of particles into antenna**
  - Optically closed screens have been used in ATC, PLT, TFR, JET, ASDEX, TFTR. The corresponding RF losses entail the use of active cooling, as in JET with Nickel screens.
  - Optically open screens and the use of a good conductor allow to reduce RF losses and to use only radiation cooling, as in JET with Beryllium screens.
- **They are also in close interaction with the Tokamak: vacuum, neutron flux, heat loads, Tritium…**



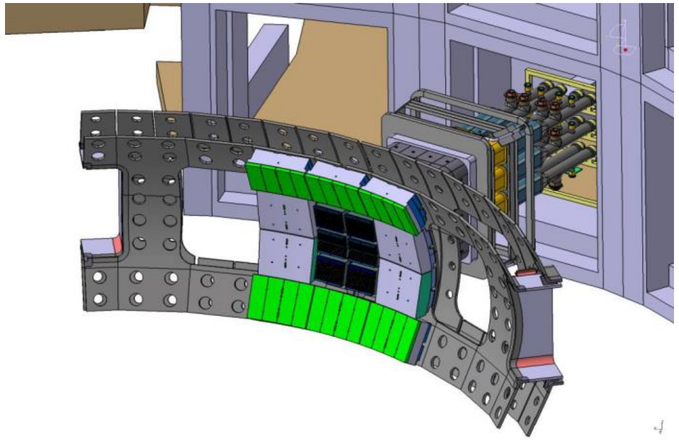
Optically closed Faraday screen



Optically open Faraday screen



Designed for long pulse (active cooling)



Antenna integrated in the Tokamak

The ICRF Systems in major fusion facilities

	LHD	NSTX	TEXTOR	AUG	DIII-D	WEST	C-Mod	KSTAR	EAST	JET	ITER
Generators	TH/CPI	CPI	TH	BBC/TH	CPI	TH	CPI	CPI	TH	TH	TH
Frequency (MHz)	25-100MHz (mainly38.5MHz)	30	25-38	30-120 (30-60 used)	30-120 (60-120 used)	40 – 76.5	50-80 (50, 70, 78, 80 utilized)	30-60	25-70	23 – 57 (excluding 39-41MHz)	40-55 (to antennas) 35-65 (on test load)
Units	6	6	2	4	3	6	4	1(4)	8	16	8 + 1 spare
Total Power installed (MW)	9 MW (6 MW connected to 4 antennas)	6	4	8	6	12	8	2(8)	12	32	24 (+3 spare), 40-55MHz
Total Power injected (MW)	3	Up to 5	3.8 (max)	7.2	4.5	10	6.2	1.9(6)	3.5	A2: 16 ILA: 4.76	20
Max Voltage (kV)	35(transmission line)	25 Vac ~18 Plasma	30-35	30	30	26	40-45	30	30	A2: 35 ILA: 42	45
Pulse length (s)	5000 Generator test	Up to 1	10	5	10	30 s	1-5	300	1000	20	3600
Antennas Number	4	1	2	4	3	3	3	1	2	4 (+1)	2

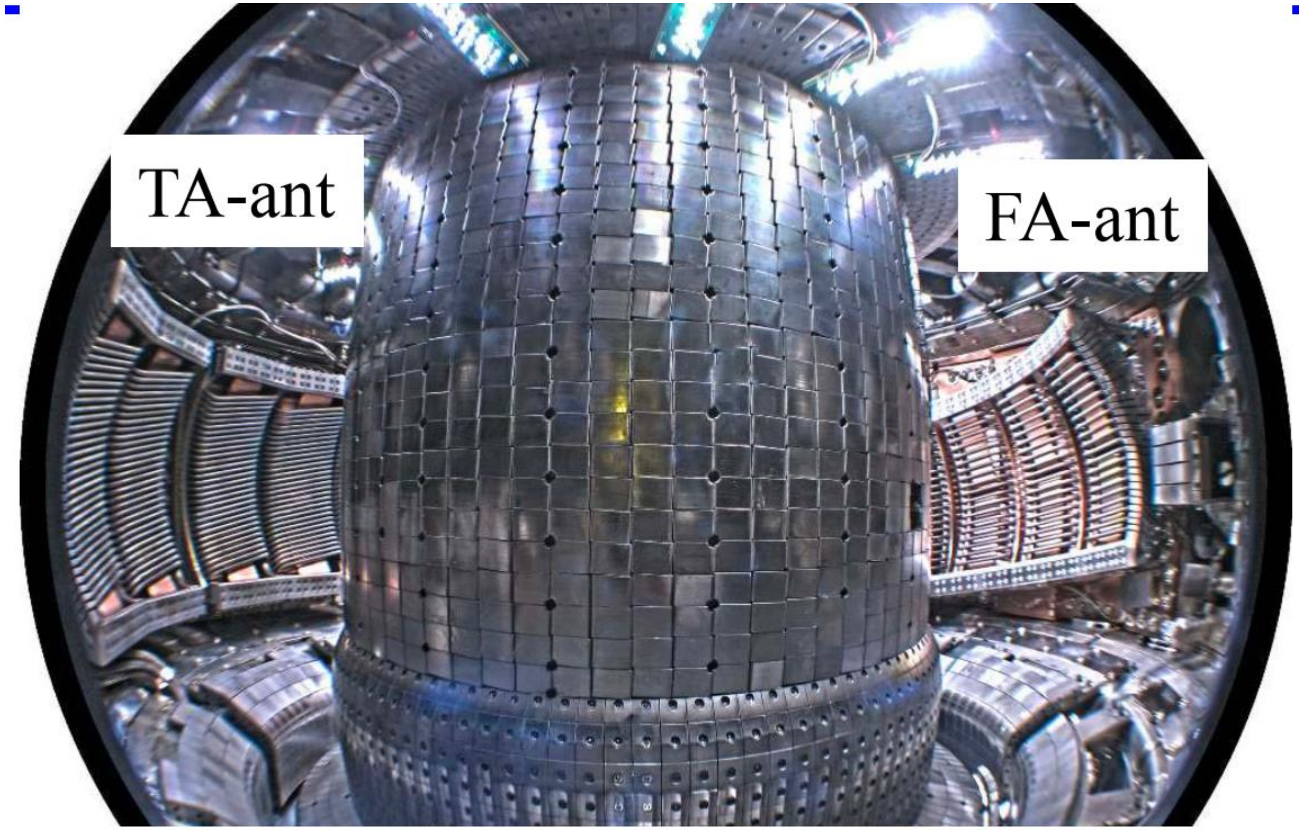
C-Mod ICRF System

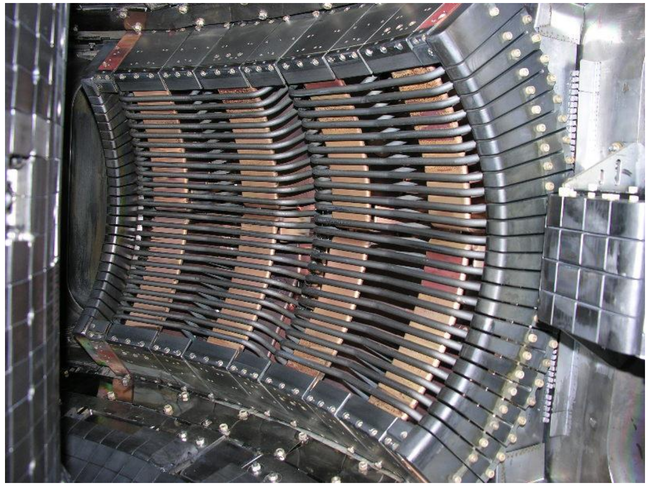
RF Cavity

RF Cavity

- Four 2.5 MW tubes (40-80 MHz)
- Two 2-strap antenna and one 4-strap antenna.

C-Mod ICRF Antennas





- Main auxiliary heating source for C-Mod
- Minority heating.
- Mode conversion heating and current drive.
- ICCD on sawtooth control
- Energetic particles study
- ICRF sheath and RF metal wall interaction.
- Alfven waves/instabilities

Field aligned antenna has replaced the conventional four-strap antenna

S.J. Wukitch,APS2012

JET ICRF System

- 32 MW RF source power
- 5 antennas
- However, the RF source utilization rate has been rather low.
- Usually about 5 MW available to plasma.

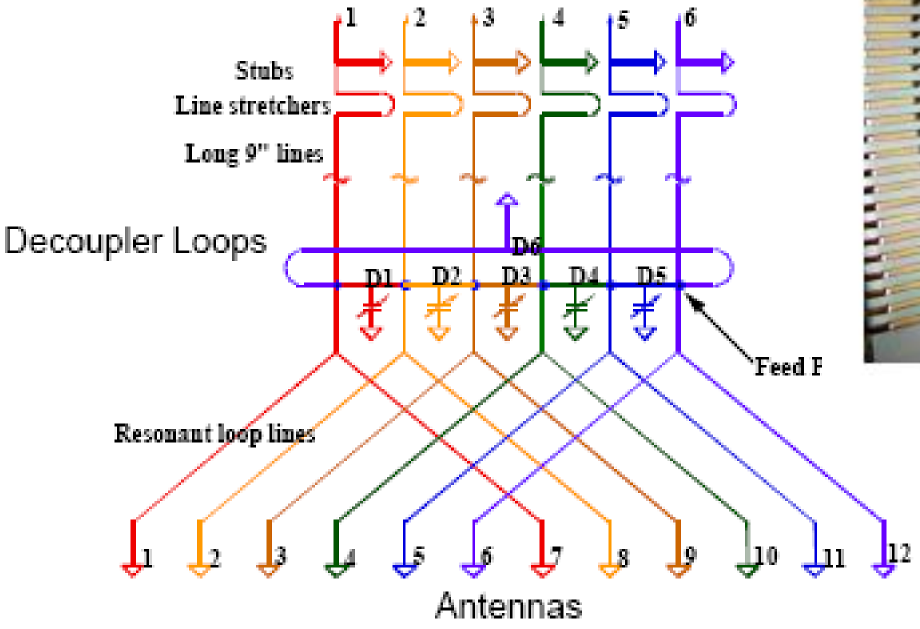
Fig. 2. (Left) Back view of the JET ITER-like antenna housing with eight attached measurement adaptors. (Right) Front view of the JET ITER-like antenna and moveable plexiglass water tank filled with salty water solution.

A new ITER like antenna being tested on JET.

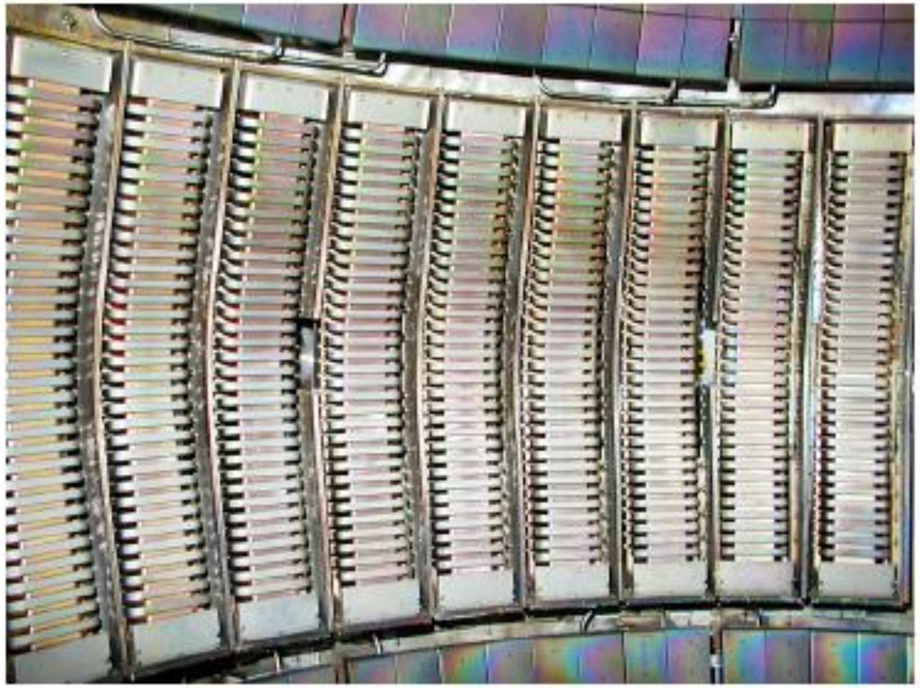
M. Vrancken, Fusion Eng. Design, 2007

NSTX HHFW System

- 30 MHz, 6 MW
- HHFW electron heating
- HHFW current drive
- Edge loss mechanism



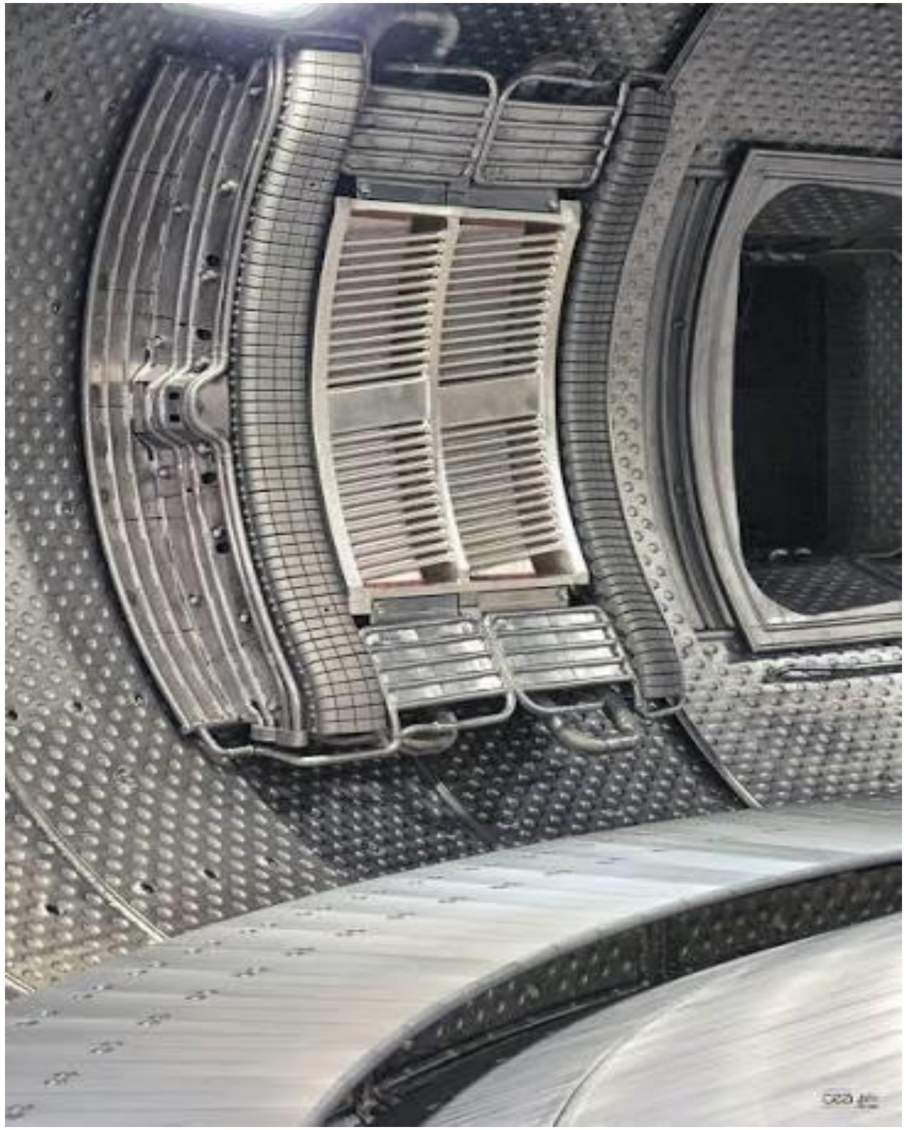
[NSTX HHFW antenna]



[Source : PPPL]

WEST ICRF System

- 3 antennas, each at 4 MW, 30-80 MHz
- Minority heating
- Antenna loading study
- Antenna and plasma interaction study
- Mode conversion study



ASDEX Upgrade ICRF System

- 4 generators, 2 MW each. Frequency from 30 to 120 MHz
- The 2 MW rf generator manufactured by ASIPP. Frequency from 24 to 61 MHz
- 4 Antennas: two 3-strap antenna and two 2-strap antenna
- Minority heating
- Antenna impurity study
- Antenna matching study

DIII-D ICRF System

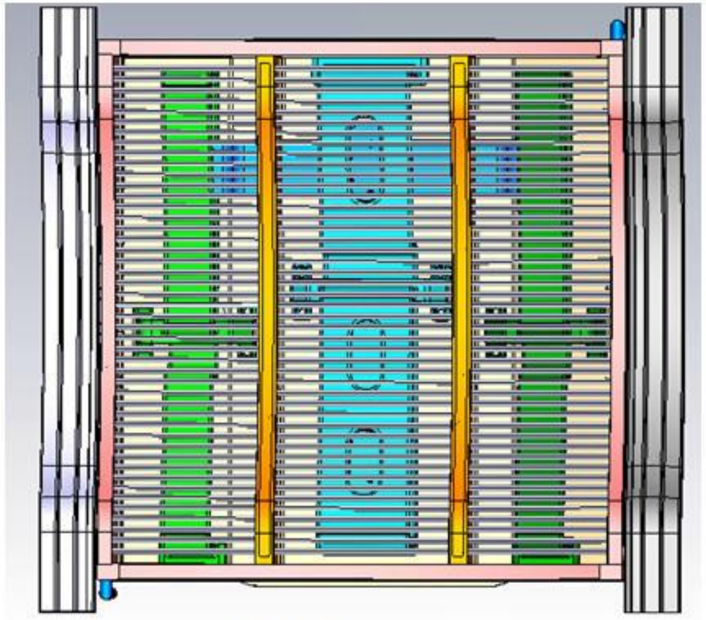
- 3 generators, 2 MW each. Frequency from 30 to 120 MHz
- Fast wave heating
- Fast wave current drive
- Fast wave and neutral beam interaction

Fig. 3. One of the two newer FW antenna arrays in DIII-D. The antenna is usable over the 60- to 120-MHz band, with a self-resonance at ~115 MHz. The array is ~0.75 m wide. Here, the Faraday shield elements are bent into a U-shape perpendicular to the plane of the picture. The protective limiter surrounding the antenna is also visible.

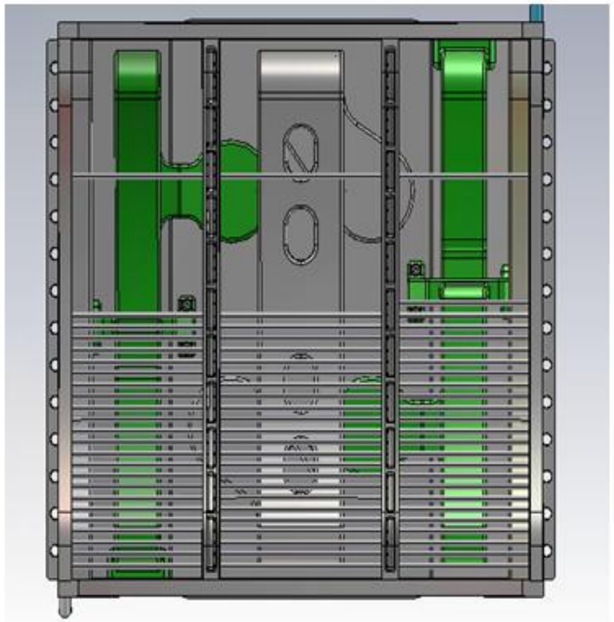
Pinsker, Fusion Science and Tech, 2005

EAST ICRF System

- 8 generators, 1.5MW each. Frequency from 25 to 70 MHz
- Two 3-strap antennas Since 2026 and 6MW connected to 2 Antennas
- Minority heating
- Antenna loading study
- Antenna and plasma interaction study
- Antenna matching study



Ant-I-port



Ant-N-port

HL-3 ICRF System

- 4 generators, 1.5MW each. Frequency from 25 to 50 MHz
- Two 2-strap antennas and 6MW connected to 2 Antennas
- For a Deuterium plasma, the hydrogen minority and the 2nd harmonic of Deuterium are the main ion heating schemes with f=33MHz at B0=2.2T.
- For a Deuterium-Tritium plasma, the fundamental He-3 and the 2nd harmonic of Tritium with f=25MHz at B0=2.5T are considered.

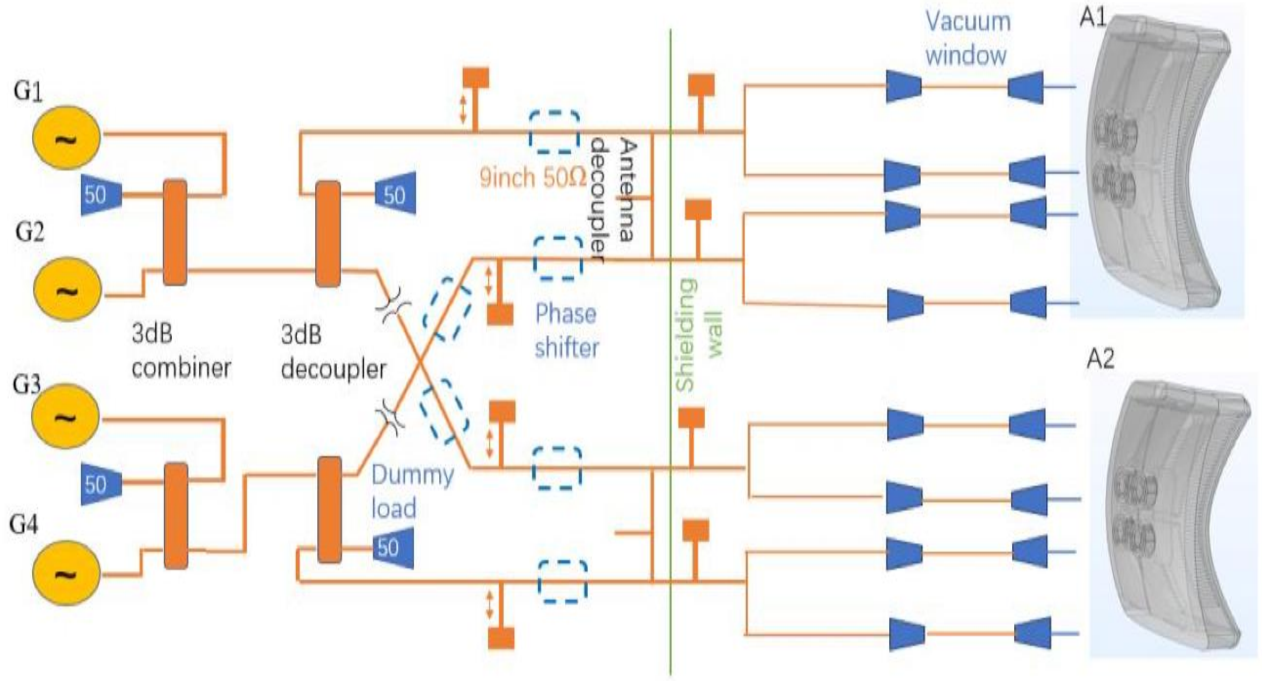
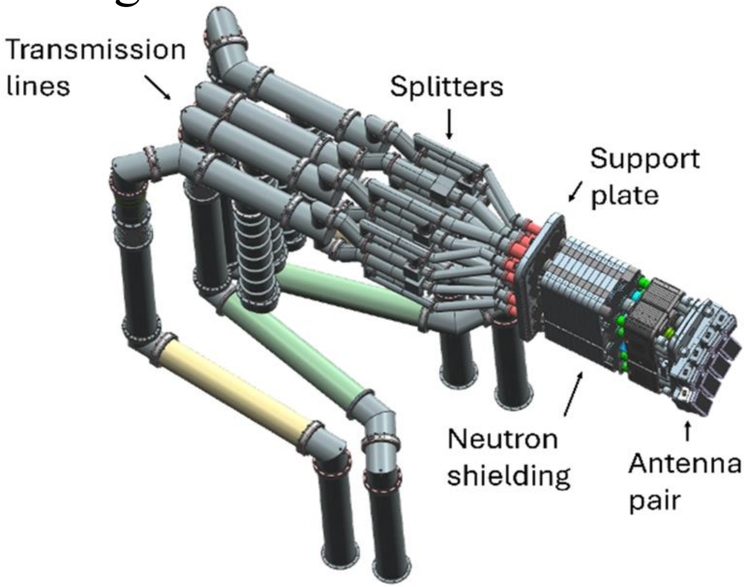


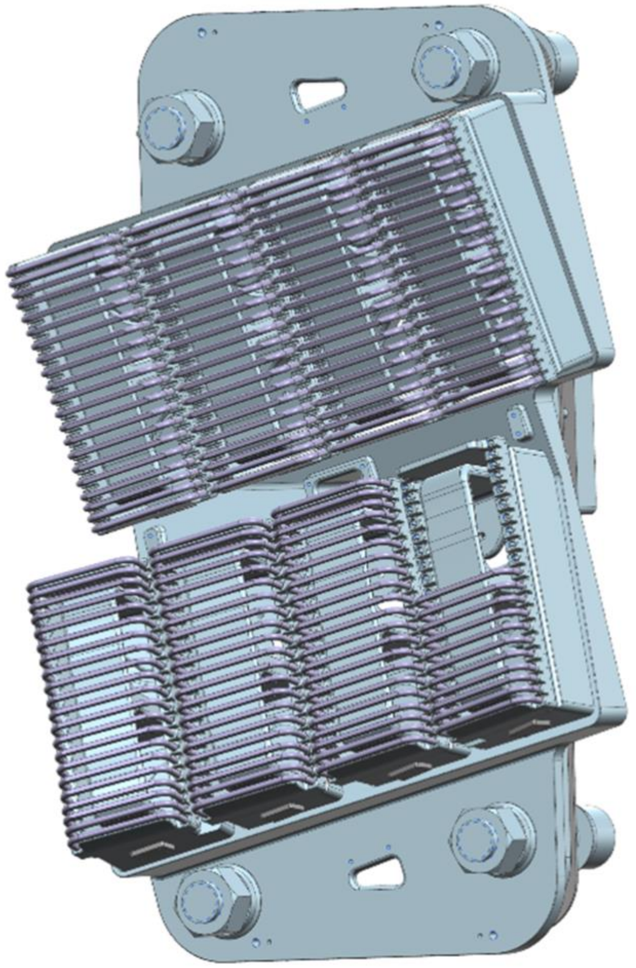
FIG 5. Sketch of the 6MW ICRF system for HL-3.

Ling-Feng Lu *et al* 2026 *Nucl. Fusion* **66** 086032

SPARC ICRF System

- 22 generators, 2.0 MW each. Frequency 120±1MHz
- 14 Antennas arranged at 7 midplane ports
- The system design allows powering a pair of antennas with up to three transmitters (one for the outer straps and one for each of the inner straps)
- ^{3}He minority and 2nd harmonic T heating at ~12 T, and H minority and 2nd harmonic D heating at ~8 T.

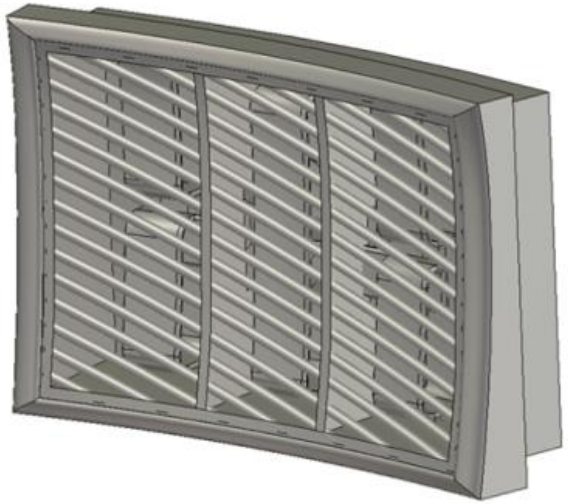


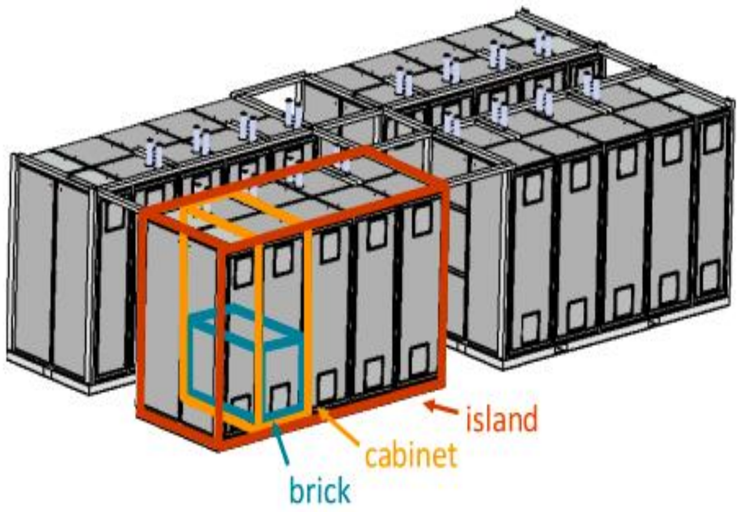


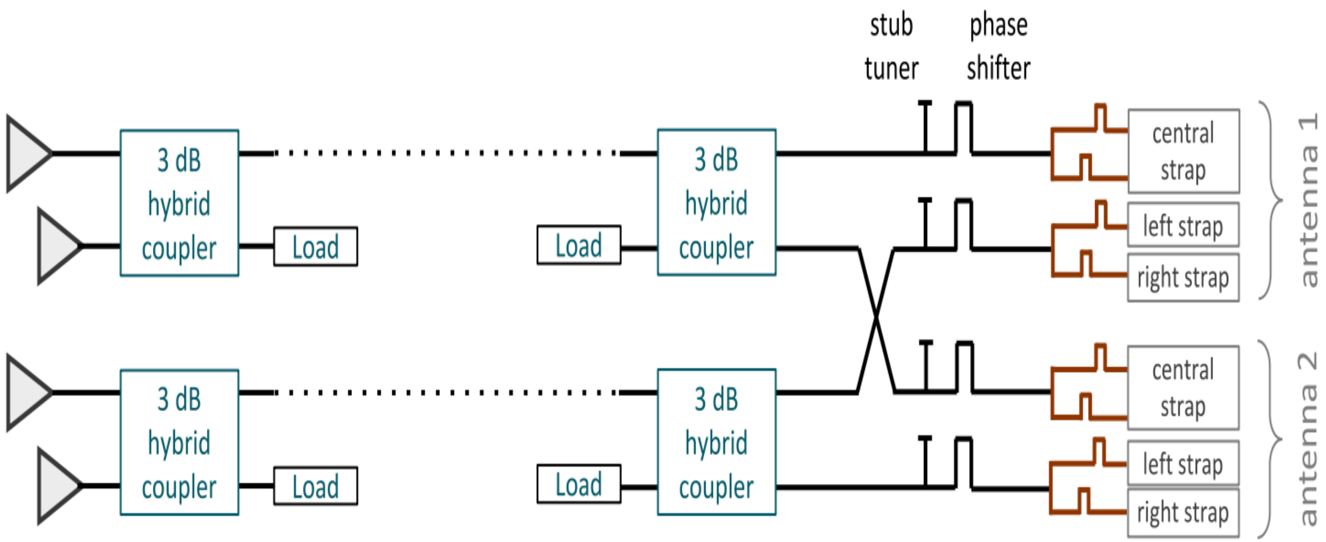
Maria Usoltseva RFPPC2025

DTT ICRF System

- 4 generators, 1.2MW each. Frequency from 60 to 90 MHz
- 2 Antennas, On axis Minority heating-D(H),D(He_3)
- In particular, grid tube technology was abandoned in favour of solid-state one, a 3-strap antenna concept was preferred, and 3 dB hybrid couplers were chosen in place of conjugate-T



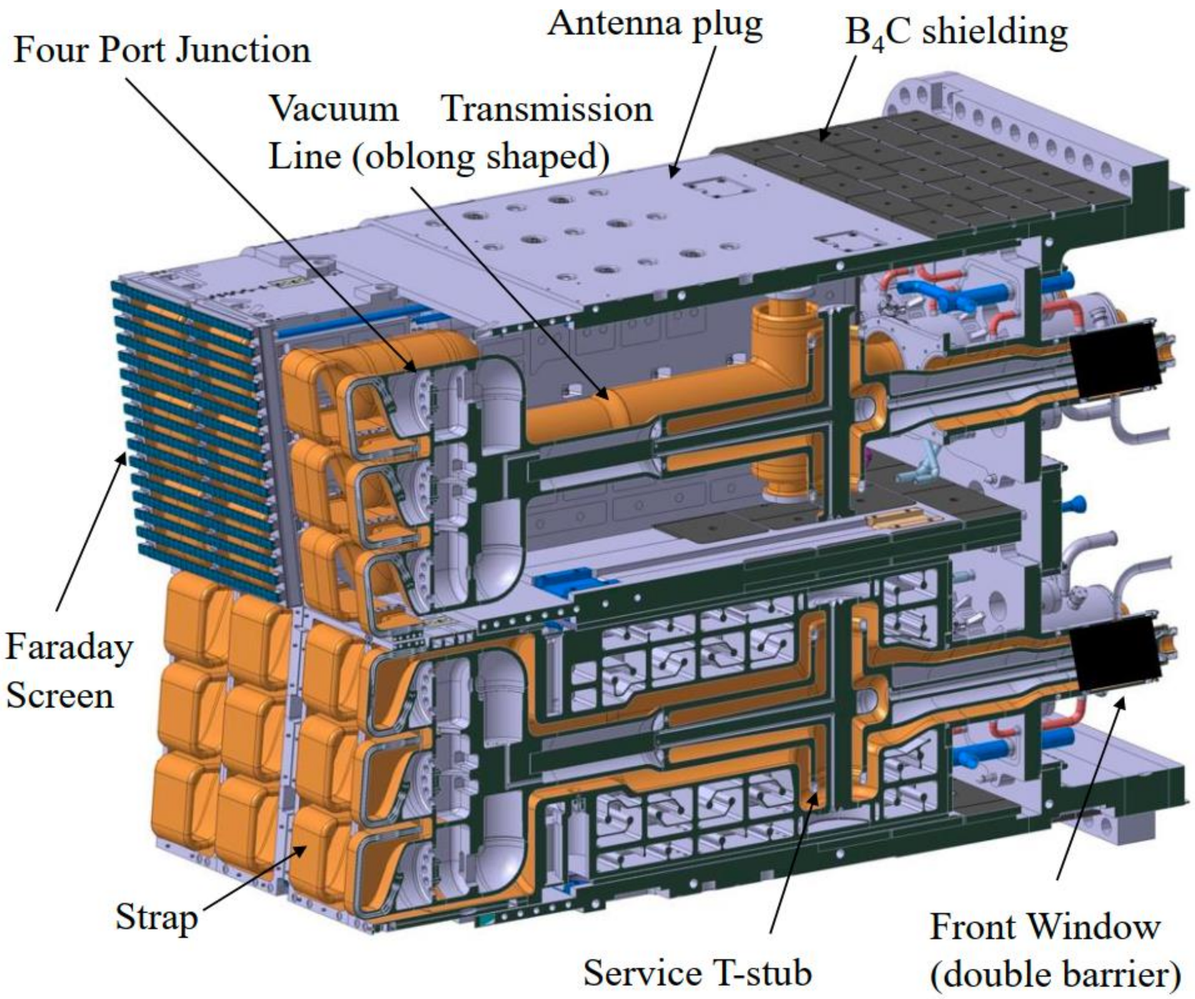




S. Ceccuzzi, FED 2025

ITER ICRF System

- 2 Antennas,each 10 MW CW, 40-55 MHz.
- 9 RF sources: 4 per antenna + 1 spare.
- Each RF source: 2 chains & 3 dB combiner
- Bulk plasma heating through minority or 2nd harmonic
- ICWC



W. Helou, CWRF2022

Contents

Typical Vacuum Tubes

- **RF power amplifiers: the vacuum tubes and the transistors.**
- **Part of the Vacuum tubes: the grid tubes, the linear beam tubes and the crossed-field tubes.**

Vacuum Tubes

Grid Tubes

Triodes
Tetrodes
Pentodes
Diacrodes

Linear Beam Tubes

Klystrons
Travelling Wave Tubes (TWT)
Gyrotrons
Inductive Output Tubes (IOT)

Crossed-field Tubes

Magnetrons

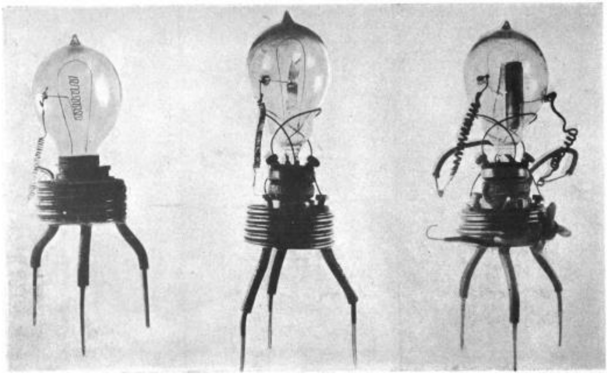
Transistors

Bipolar Junction Transistor (BJT)
Field Effect Transistor (FET)
Junction Gate FET (JFET)
Metal Oxide Semiconductor FET (MOSFET)
power MOSFET
Vertically Diffused Metal Oxide Semiconductor (VDMOS)
Laterally Diffused Metal Oxide Semiconductor (LDMOS)
Silicon Germanium (SiGe)
Gallium Arsenide (GaAs)
Gallium Nitride (GaN)

E. Montesinos, CERN Accelerator School Proceedings, 2024
Power Vacuum Tubes Handbook 2nd Edition

Tetrodes

- 1904 Diode, John Ambrose Fleming
- 1906 Audion (first triode), Lee de Forest
- 1912 Triode as amplifier, Fritz Lowenstein
- 1913 Triode 'higher vacuum', Harold Arnold
- 1915 First transcontinental telephone line, Bell
- 1916 Tetrode, Walter Schottky
- 1926 Pentode, Bernardus Tellegen
- 1998 Diacrode, Thales Electron Devices

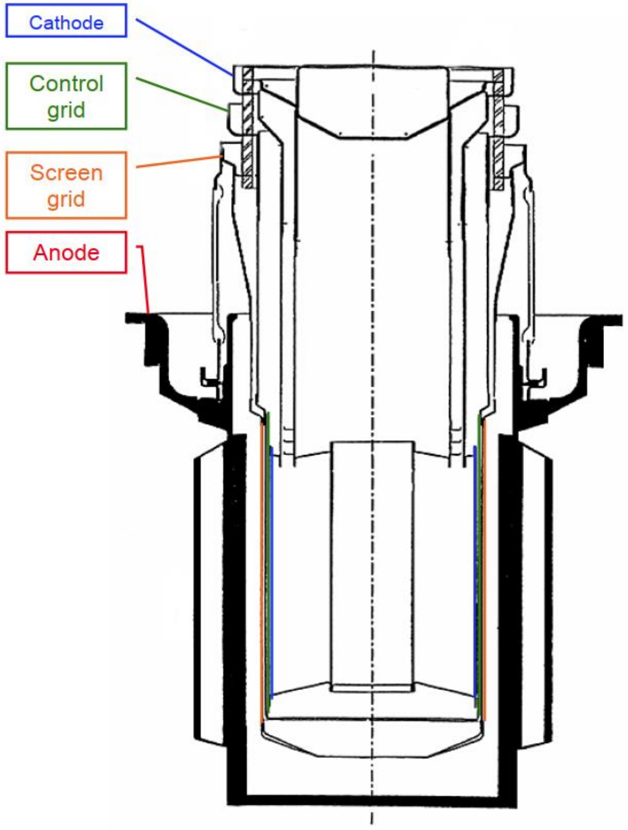


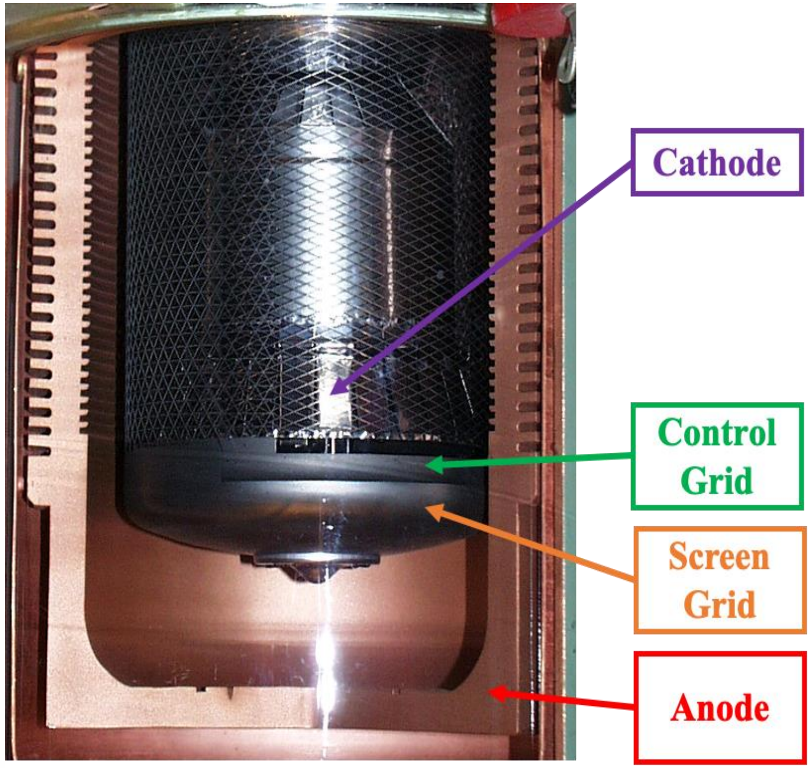
The first diode prototype
Fleming Diode, 1904

Thales TH628 Diacrode, 1998

Structure of Tetrode

- A vacuum tube is a sealed tube containing vacuum which allows free passage of electric current
  - ✓ **The cathode** is the electrode that contains the heating source from which electrons are released
  - ✓ **The anode** is the electrode that receives those electrons thus providing an electric path in the tube
  - ✓ **The grids** is an additional electrode by which the current flowing in the anode circuit can be controlled by another potential





R.G.Carter CERN, 2013

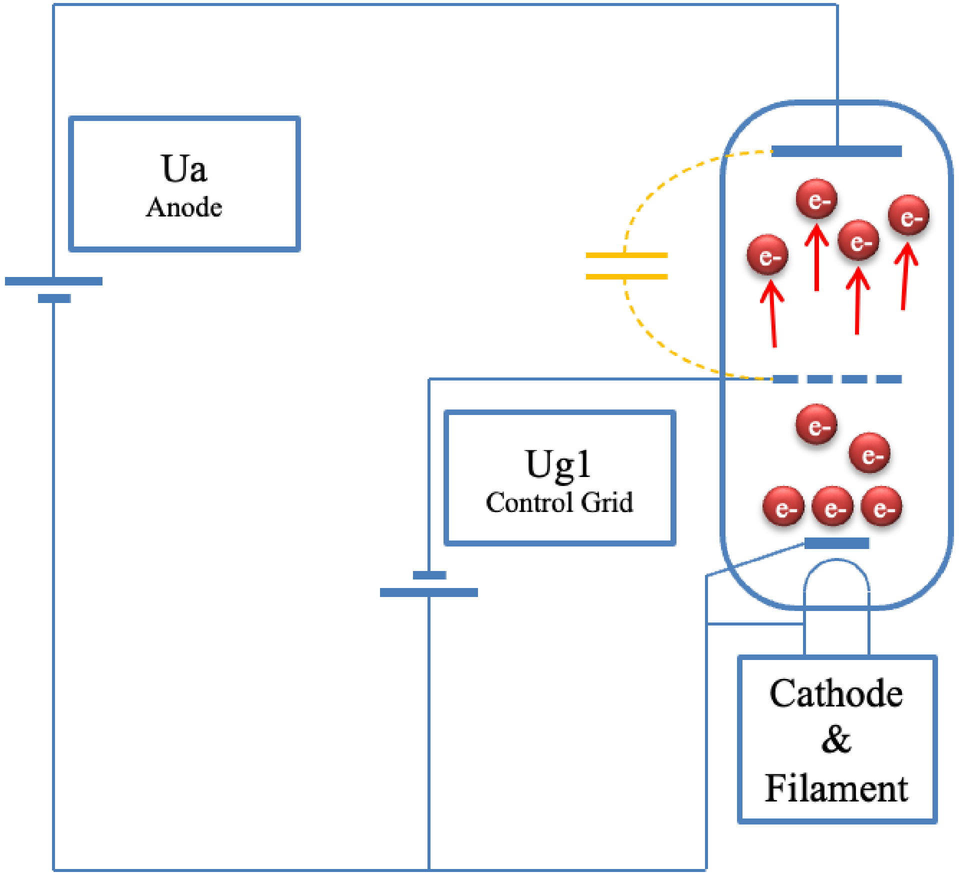
Basics of Grid Tube

From triode to tetrode amplifier

Triode

- Modulating the grid voltage proportionally modulates the anode current
- Placing **a negative voltage** onto **the grid** will have the effect of repelling some electrons back to the cathode
- **Limitations**
  - ✓ Parasitic capacitor Anode/g1
  - ✓ Tendency to **oscillate**

The triode has drawbacks in terms of gain and stability due to feedback between the anode and control grid circuits caused by internal capacitance



E. Montesinos, CERN Accelerator School Proceedings, 2024
Power Vacuum Tubes Handbook 2nd Edition

Basics of Grid Tube

☐ From triode to tetrode amplifier

- ✓ The introduction of the screen grid reduces the anode-control grid capacitance and hence the feedback
- ✓ This improves the gain and stability

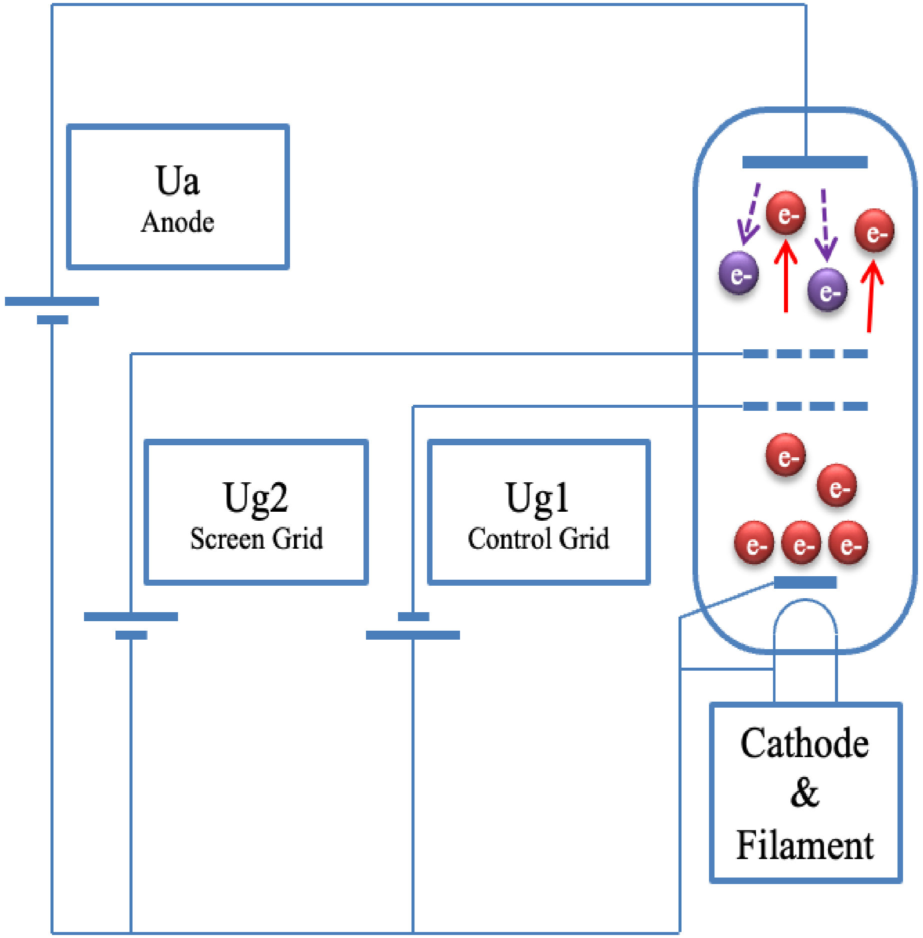
Tetrode

☐ Screen grid

- ✓ Positive (lower anode)
- ✓ Decouple anode and g1
- ✓ Higher gain

☐ Limitations

- ✓ Secondary electron
- ✓ Anode treated to reduce secondary emission

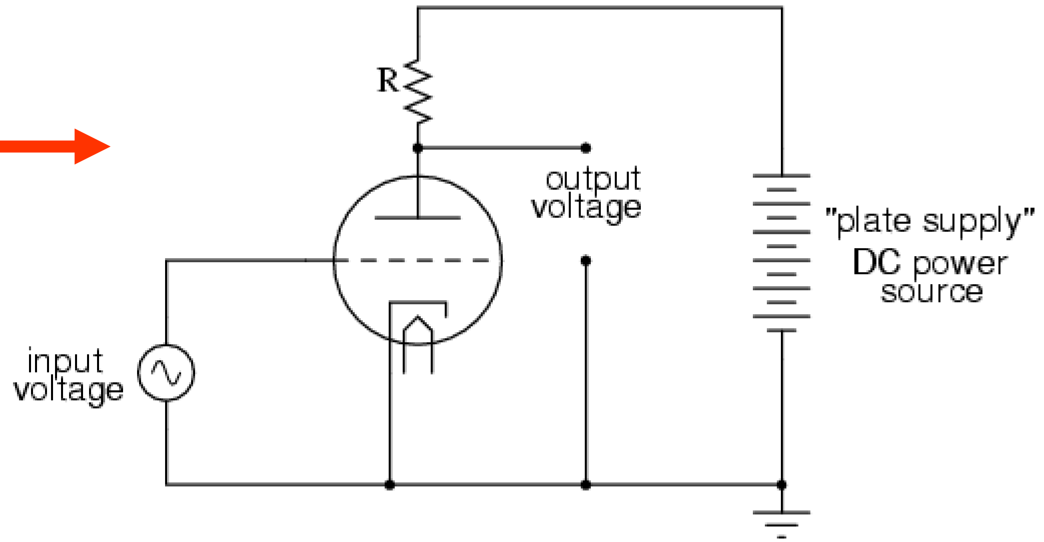


E. Montesinos, CERN Accelerator School Proceedings, 2024
Power Vacuum Tubes Handbook 2nd Edition

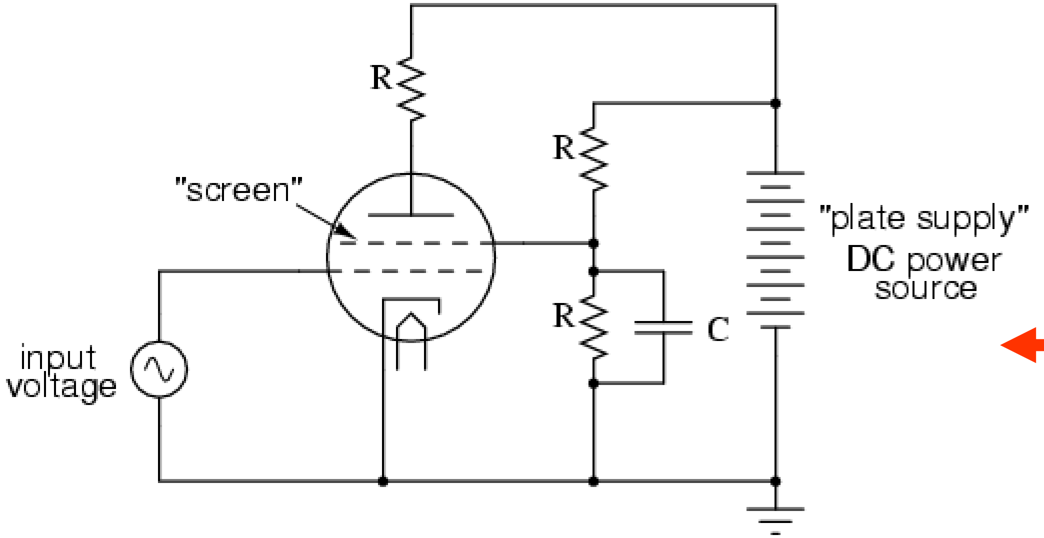
Vacuum Tubes based power amplifier : Triode and Tetrode

Low power triodes (~ 10 kW) can now be completely replaced by solid state amplifiers.

Triode amplifier circuit



Tetrode amplifier circuit



For power above ~10 kW, we use tetrodes for power amplifier

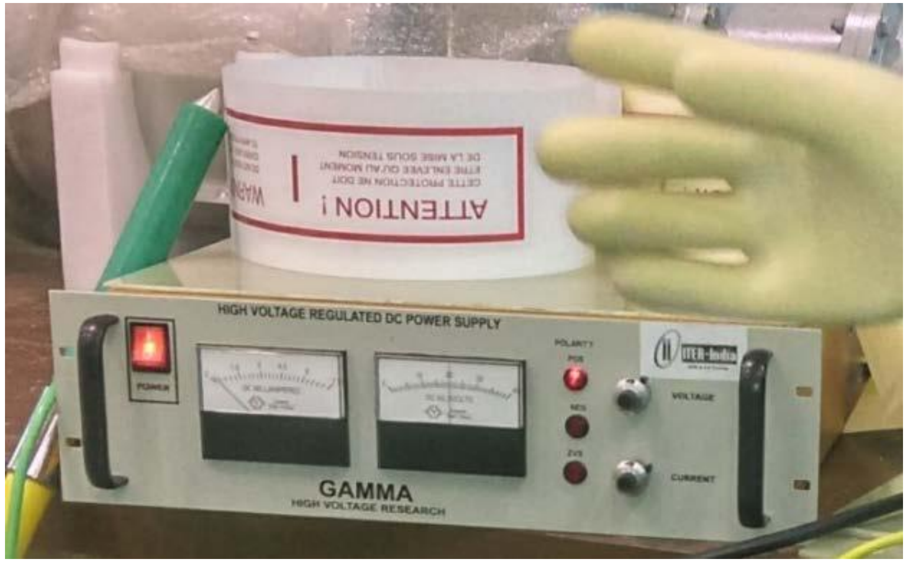
Typical Tube Specifications

☐ Gain & Power Level：Amplification: mW to MW

Modules	Max. Gain	Expected Gain	Input Power Level	Max. Output Power Level
LPA (wide band solid state)	50dB	50-45dB	3-10mW	300W /chain
HPA-1 (TH595/4CW25000B)	20dB	17-18dB	240-190W	15kW /Chain
HPA-2 (TH781/4CW150000E)	14dB	12-13.5dB	8.0-5.6KW	125kW /Chain
HPA-3 (TH628/4CM2500KG)	14dB	11-13.5dB	120-67KW	1.5MW /Chain

Hi-pot Test

- Before inserting the tubes in the cavity Hi-pot test was conducted on the tube



Description	Voltage	I leakage	Comment
K (gr.)- G1	5 kV	0	OK
G1 (gr.) - G2	5 kV	0	OK
K,G1,G2 - Anode (gr.)	20 kV	~ 200 μA	OK

🔥 **Increase the radius of test aera to 5 meters for 50kV**

- Open tube didn't test beyond 15-20 kV due to possibility of X-Ray exposure

Thales, HV Tests ,2021

Operation & Possible failures

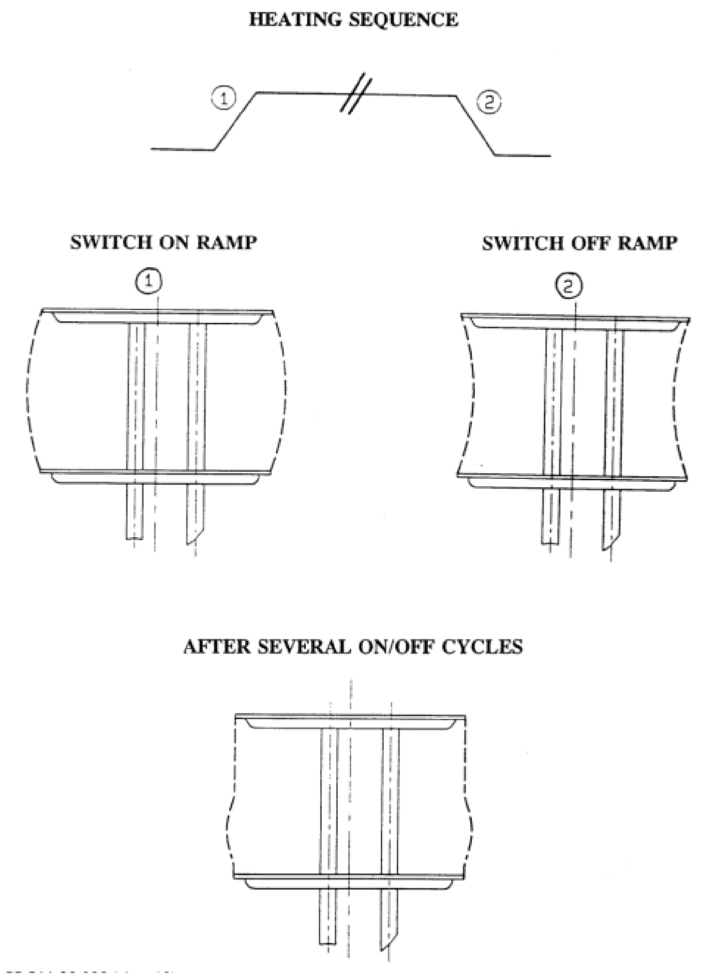
Factors of influence	Damage in the tube	Limiting factors
Cathode temperature	Cathode deformation Cathode decarburization	Filament voltage too high Dissipated power on the grids RF losses due to harmonics
Cathode cycling	Cathode deformation	More than one on/off cycle per day Mains failure
Overvoltage and Overcurrent	Grids damaged due to flashes between KG1 or G1G2	Bad tuning Accidental circuit mismatch Defective protective devices Defective damping circuits
Overheating	Outgassing or even melting of the anode or of the base of the tube	Bad cooling Bad tuning Accidental circuit mismatch
Vacuum	Drop of emission	Bad contacts Corrosion Overheating

E.Montesinos, CAS course on "RF for Accelerators"

Cathode

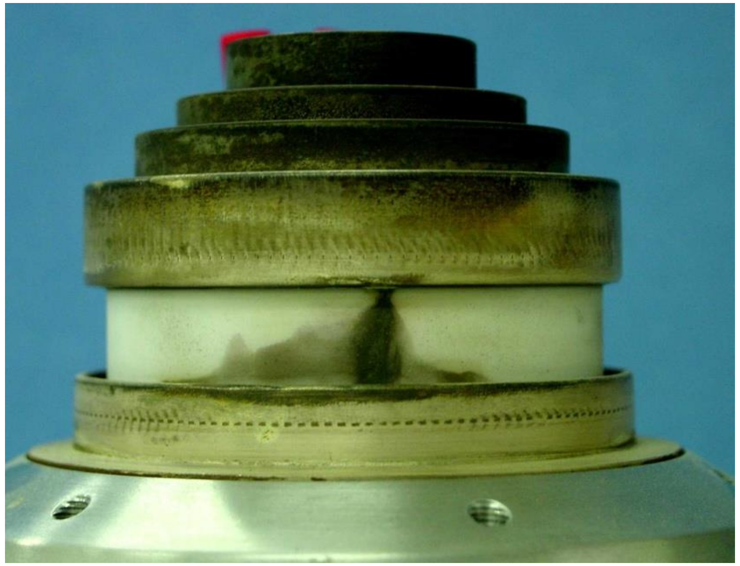
- Greater the cathode temperature T, strictly linked to filament voltage, less the cathode lifetime

- **Too high cathode temperature**
  - Accelerate decarburization process
  - Tends to **deform cathode shape**
- **Too low cathode temperature**
  - Reduce thermal electrons flow
  - Slow down the process of thorium diffusion to the surface
- **As a rule of thumb, - 5 % Filament Voltage → + 25 % lifetime**

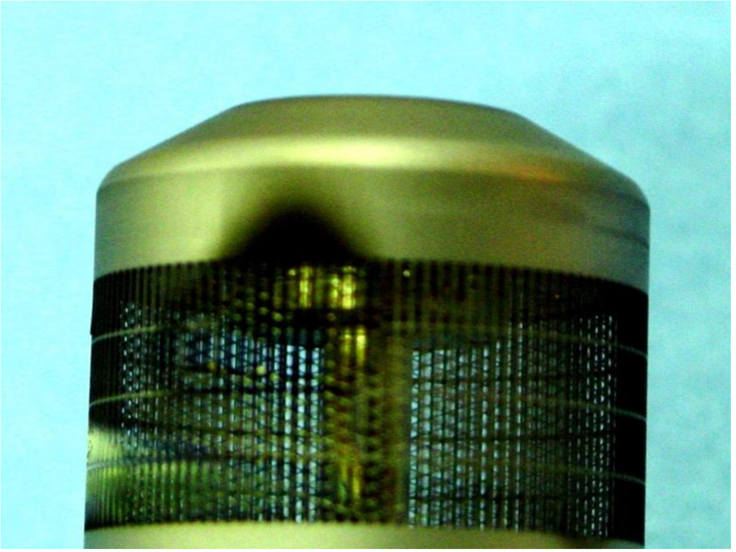


E.Montesinos, CAS course on "RF for Accelerators"

- Heater voltage, always with gradual application and gradual shutdown
- The ramp allows cathode assembly, cathode and its support, to absorb differences caused by thermal expansion
- Tube lifetime depends on the duration of the ramp, and on the on/off cycling frequency as well
- It is advised to keep heater voltage to nominal, during short transmitter interruptions



External arcing between Anode and G2



Internal arcing on G2

Overheating due to lack of air cooling

Ceramic crack due to internal metallization of the ceramic, perhaps due to over filament

E.Montesinos, CAS course on "RF for Accelerators"

Theoretical efficiency

Because the amplifier is never completely efficient there is always some conversion of energy into heat. The greater part of the heat is dissipated in the anode of a tetrode

- **The principle of conservation of energy requires that, in the steady state, the total input and output power must balance, that is**

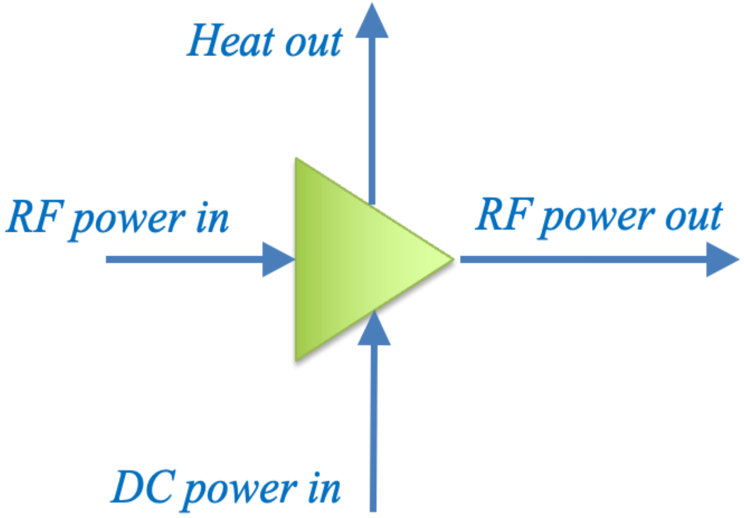
$$P_{RF\ in} + P_{DC\ in} = P_{RF\ out} + Heat$$

- **The efficiency of the amplifier is the ratio of the RF output power to the total input power**

$$Efficiency = \frac{P_{RF\ out}}{P_{DC\ in} + P_{RF\ in}} \approx \frac{P_{RF\ out}}{P_{DC\ in}}$$

- **The other main parameter of the generic amplifier is its gain in decibels given by**

$$Gain(dB) = 10\log_{10}\left(\frac{P_{RF\ out}}{P_{RF\ in}}\right)$$



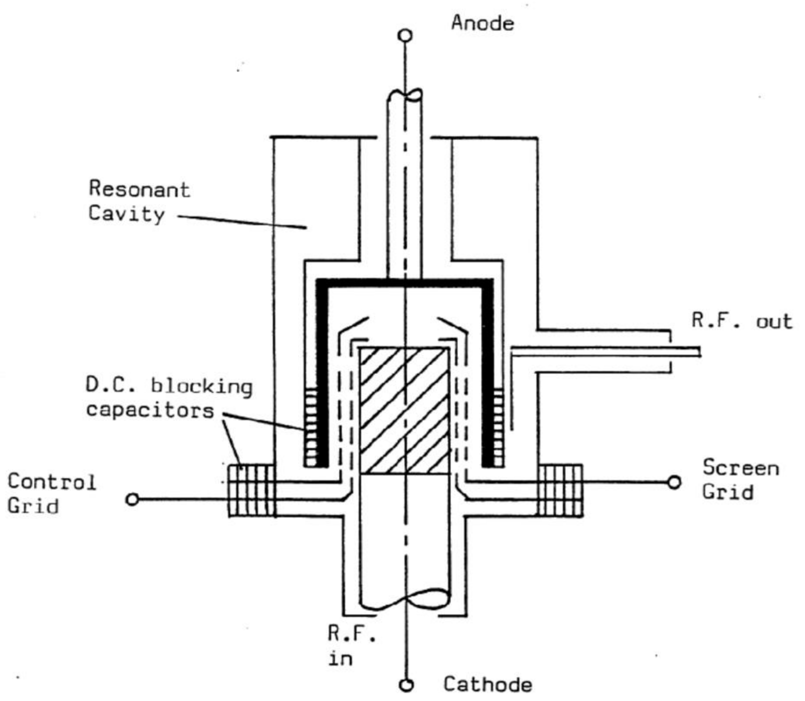
R.G.Carter CERN, 2013

Tetrodes for fusion: Gain is usually 13-15 dB and efficiencies between 50 % and 70 %.

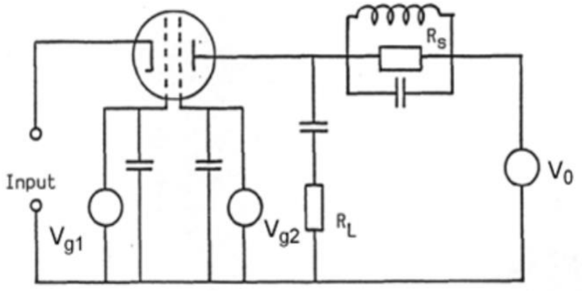
R.G. Carter, R.F. power generation, Proc. of the CERN Accelerator School, 2010

General Principles of Tetrode Amplifier

- ☐ **The tube is operated in the grounded grid configuration**
  - ✓ with coaxial input and output circuits.
  - ✓ Grids held at RF ground isolate input from output
- ☐ **The outer conductors of the coaxial lines are at ground potential**
  - ✓ Separated from the grids by d.c. blocking capacitors
- ☐ **The anode resonator is a re-entrant coaxial cavity**
  - ✓ Separated from the anode by a d.c. blocking capacitor
- ☐ **The anode HV connection and cooling water pipes are brought in through the centre of the resonator**
- ☐ **Output is capacitively or inductively coupled**



Arrangement of a tetrode amplifier

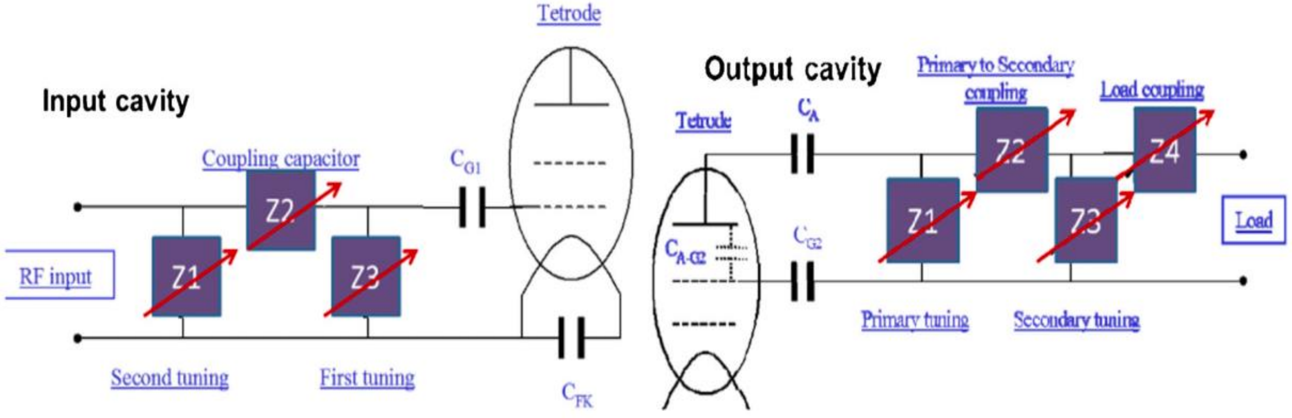


Circuit of a grounded-grid tetrode amplifier

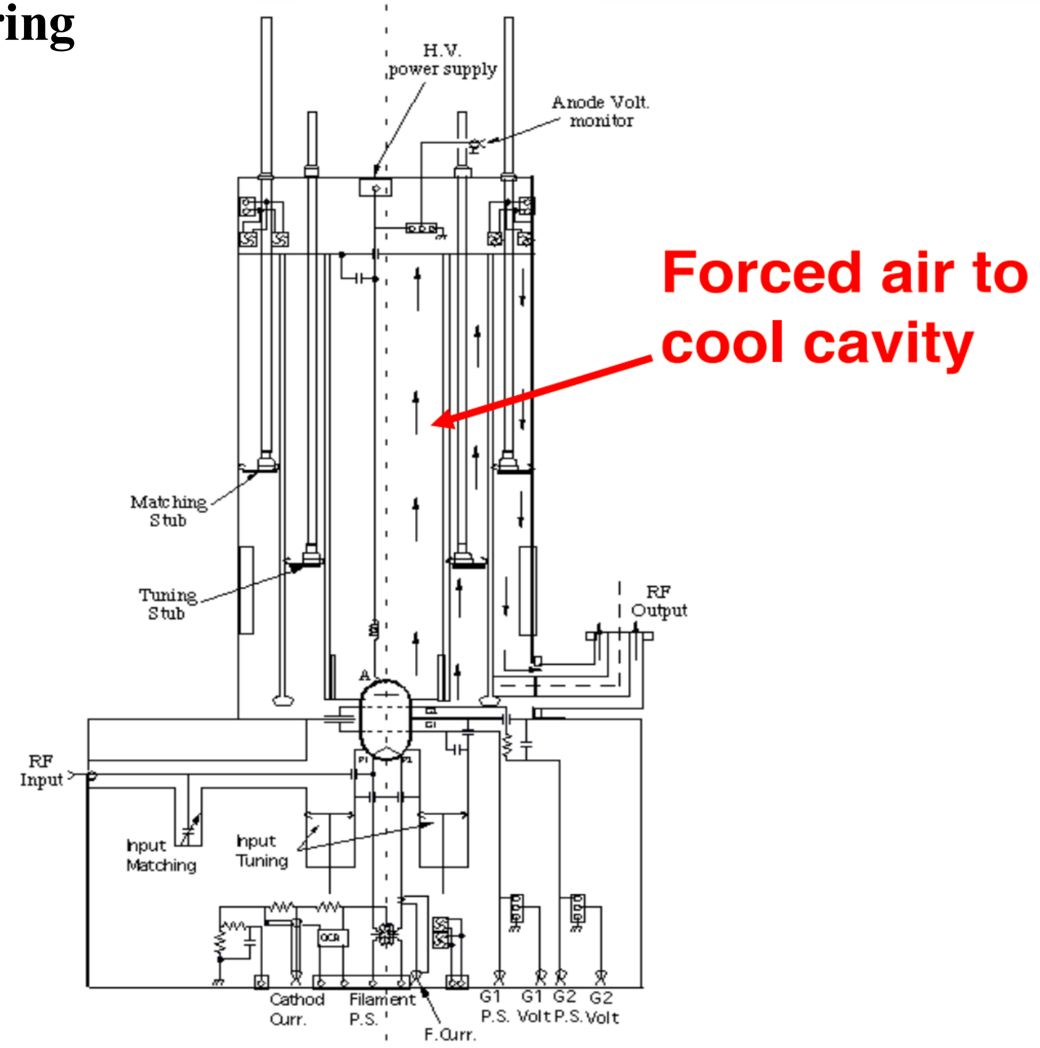
R.G.Carter CERN, 2013

Example of Tetrode Amplifier

- **The input and output cavities need a special design considering the wideband requirement of operation.**
- **High Power of RF Generator with Wide frequency Range**
  - ✓ **Output**: Double coaxial cavity ～4m in length!
  - ✓ **Outside:** Matching stub tuner.
  - ✓ **Inside:** Tuning stub tuner
  - ✓ Frequency range:25MHz < f < 100MHz
- **DC bias conditions relative to cathode**
  - ✓ Anode voltage positive
  - ✓ Screen grid positive (~ 10% Va)
  - ✓ Control grid negative



Design concept of input and output cavities



FPA cavity at LHD and EAST

Amplifier Classes

- **The operation of tuned amplifiers is designated as class A, B or C according to the fraction of the RF cycle for which the tube is conducting.**

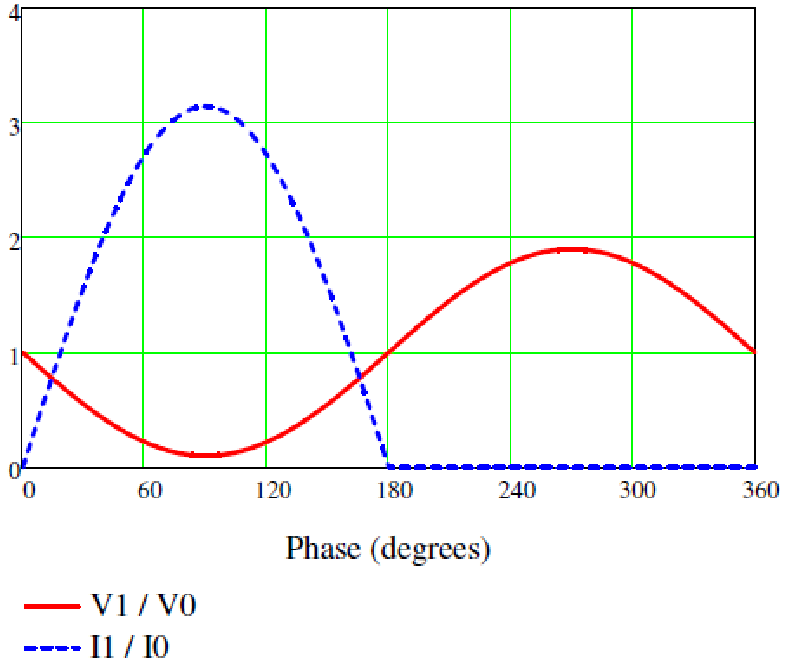
Table 2: Classes of amplifier

Class	*Conduction angle*	*Maximum theoretical efficiency*	*Negative grid bias increasing*	*Gain increasing*	Harmonics increasing
A	360°	50 %			
AB	180° to 360°	50 % to 78 %			
B	180°	78 %			
C	< 180°	78 % to 100 %			

- **Class B usually used for Fusion**

Class B operation

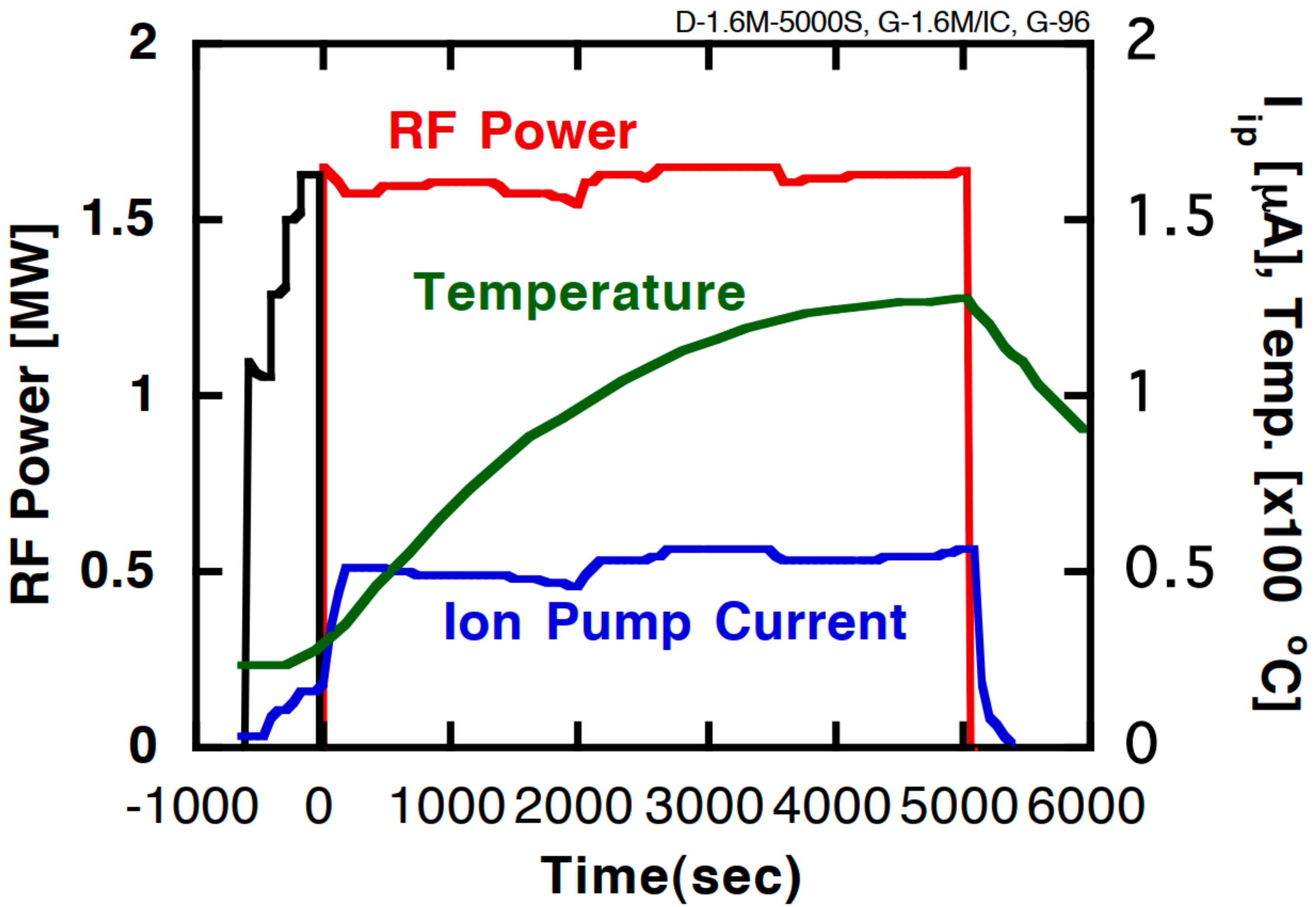
- Amplifiers for fusion are normally operated in, or close to, class B in which the tube conducts for half of each cycle.



- Control grid bias set so that anode current is zero when no RF input
- This ensures that the tube only conducts during the positive half-cycle of the RF input voltage
- Conduction angle = 180°
- Resonant circuit makes anode voltage variation sinusoidal
- Va > V_{g2} always
- Theoretical efficiency ~78%

Steady-state High Power Generator in LHD

- Test of RF generator using dummy load: 1.6MW/5,000s/f=50MHz
- Ion pump current is a monitor in the vacuum tube: 0.6μA is low vacuum pressure for operation.
- Increase in temperature of co-axial transmission line is up to 100°C with air flow of 2m/s.



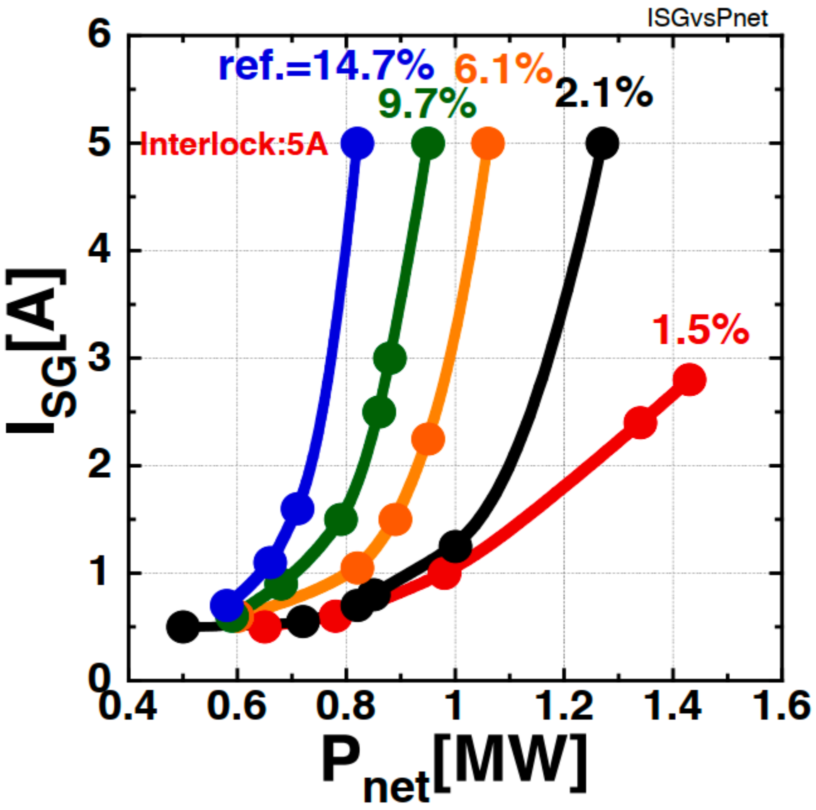
R.Kumazawa, US-EU-Japan RF Technology Workshop 2009

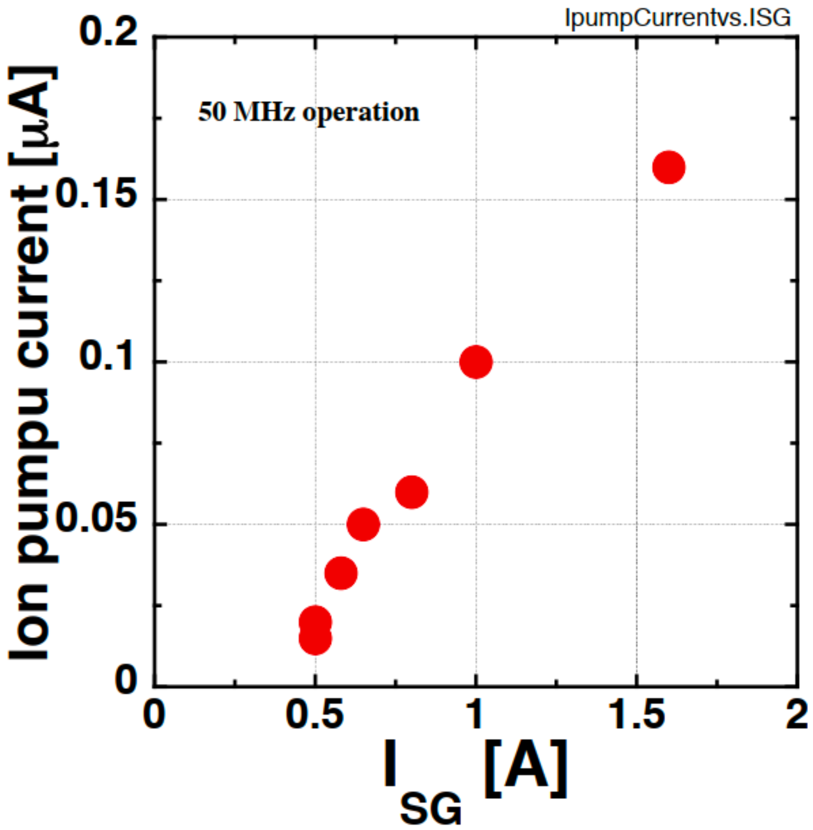
The Limits of Tetrodes Capability

- Gridded tubes operation at high frequency, long pulse regime, is limited by internal RF losses.
- Additionally, VSWR can be critical, especially if under any phase

The Limits of Tetrodes Capability

- **Dependence of Limitation of RF power output on fraction of reflected RF power**
  - (Ref.):1.5%< Ref. <14.7% (1.3<VSWR<2.2)
- **I_{SG} is increased with ref. =>then RF output power is limited with Interlock (I_{SG},<5A).**





- **Ion pump current is an important parameter to indicate the pressure in the vacuum tube.**
- **There is a close relation between screen grid current, I_{SG} and Ion pump current.**

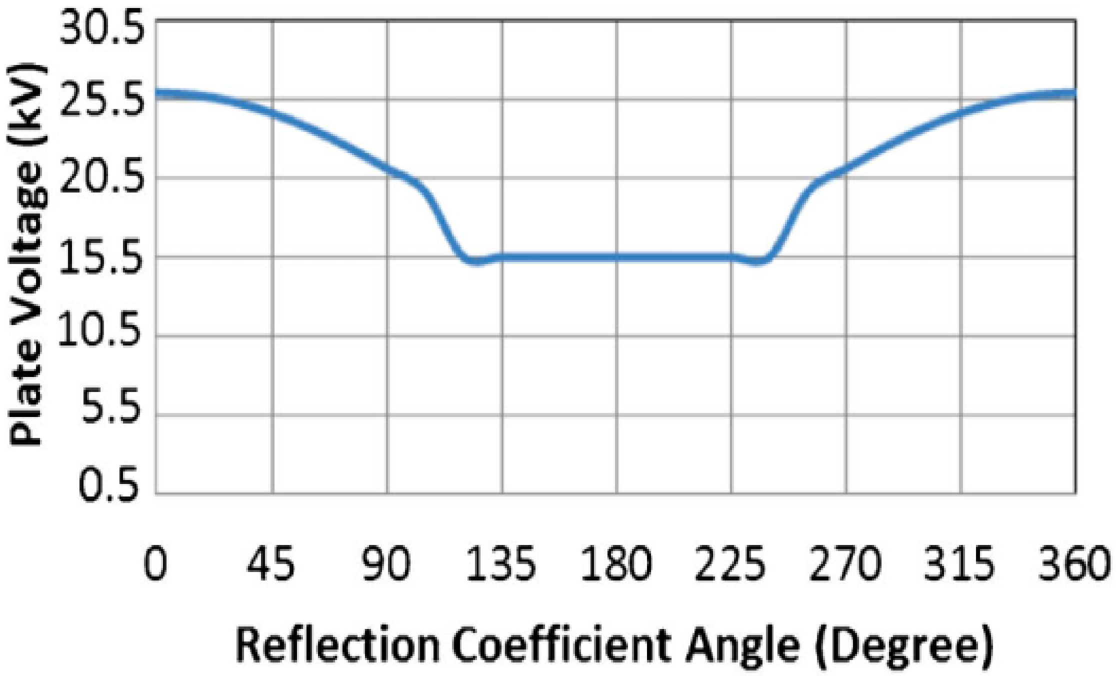
The Limits of Tetrodes Capability

Though tetrode has a significant improvement in isolation between the anode and grid circuits. It has a big drawback

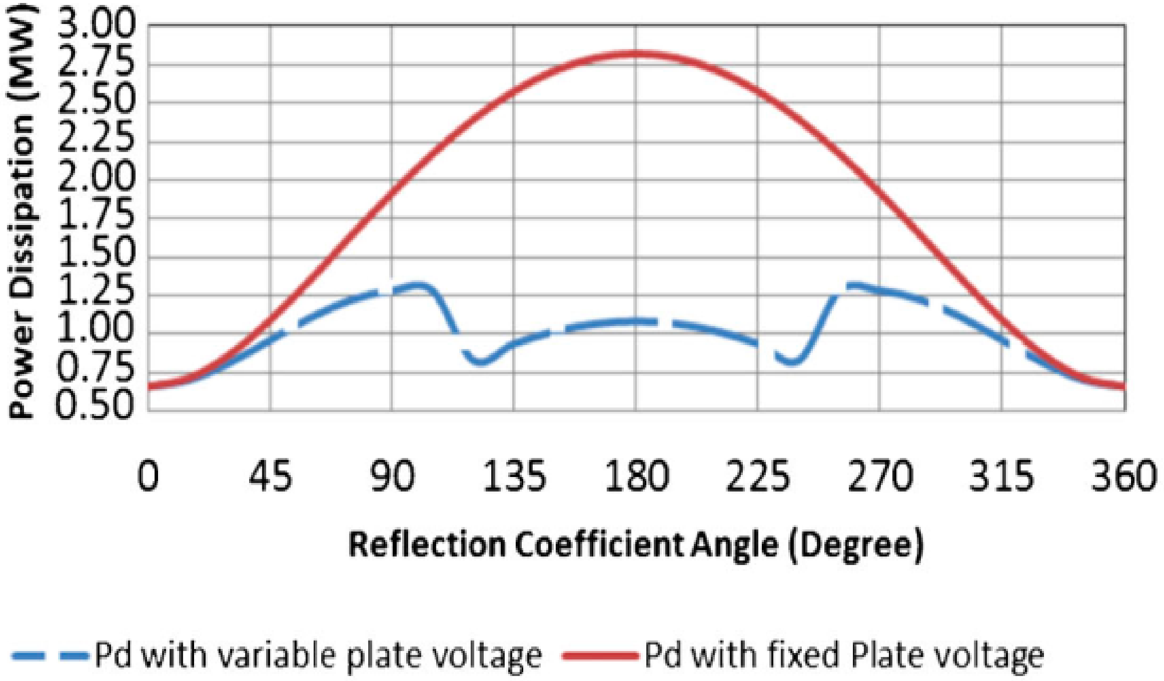
- **Tetrodes suffer from secondary emission.**
  - The electrons reaching the anode at high velocity strike other **electrons knocking them off the anode.**
  - This is known as secondary emission.
- **The introduction of the screen grid in tetrode adds another positive element in the tube which may attract the electron.**
  - These **electrons** coming from **the anode** cause **an undesirable anode to screen current**

Management of excess Anode dissipation by dynamic control of the Anode voltage

- The output power will be influenced by the VSWR with any phase
  - ✓ For estimation purposes, analysis has been conducted at a constant 1.5-MWwith VSWR=2
- **This calculation shows**
  - ✓ Around **180-deg reflection angle**, plate dissipation will exceed the maximum limit of the tube
  - ✓ **Dynamic control of the plate voltage is essential**



(a)



(b)

Max Plate dissipation < 2.5 MW

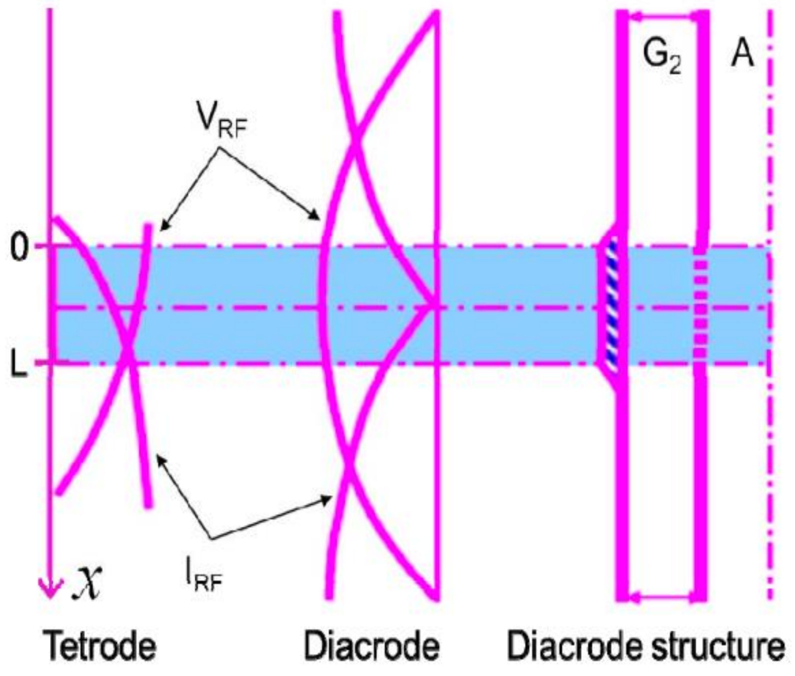
The limits of tetrodes capability

Behaviour with frequency

- The ratio between the tube dimensions and the wavelength at the operating frequency determines the distribution of voltage and current along the electrodes

This has two consequences :

- From the top to the bottom, **electron flow and dissipated power** are **not constant**. Therefore, the tube is not used with maximum efficiency.
- The current distribution generates a non-uniform RF losses distribution along the grid. **The maximum is at the bottom of the latter.**



G.Clerc, 1992 IEEE
G.Clerc, 1998 IEEE
A.Boussaton, 2014 IEEE

TH 628L Diacrode Concept

- The way to reduce the RF losses and balance the electronic flow is to tune the amplifier so as **maximum RF voltage** be located in the middle of the tube's active zone
- This leads to **double ended grid tube** and the necessity to tune the device in half wavelength.
- Also, **RF losses on grids can be expressed as:**

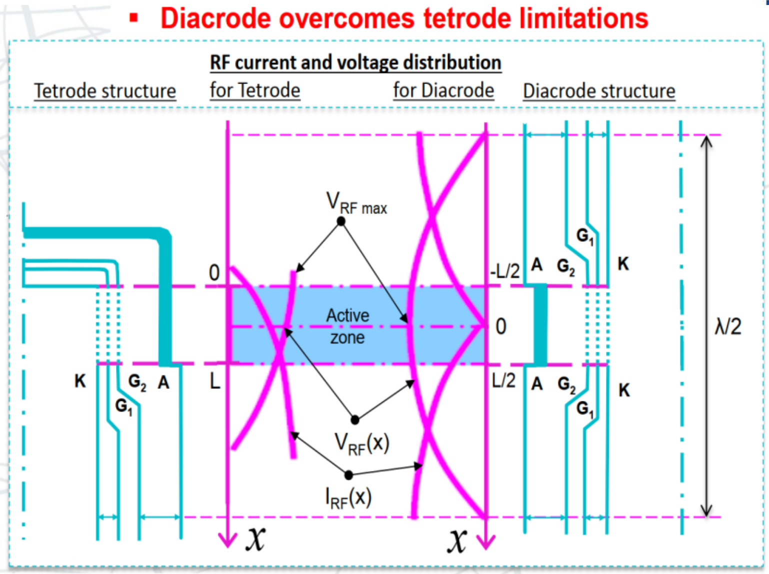
$$P_{loss\_max\_tetrode} = P_{loss}(L) \text{ and}$$

$$P_{loss\_max\_Diacrode} = P_{loss}(L/2)$$

With $$P_{loss}(x) = K \cdot V_{RF}^{2} \cdot f^{\frac{5}{2}} \cdot x^{2}$$

- Consequently, Diacrode's RF losses at the bottom of the active zone are divided by nearly four compared to tetrode, allowing margin in the use of the tube

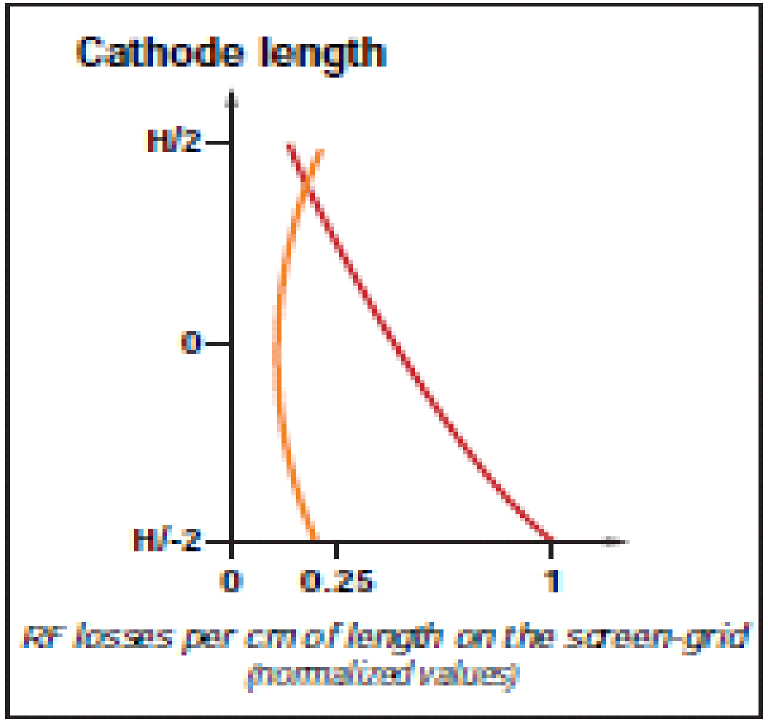
From tetrode to Diacrode, max RF losses are divided by 4 !



Diacrode (right) vs. tetrode: RF distribution comparison (left)

TH628L Diacrode as a key component for fusion

- **Example of calculated RF losses on the screen grid for the same cathode length at an output power of 1.4 MW cw @ 120 MHz**

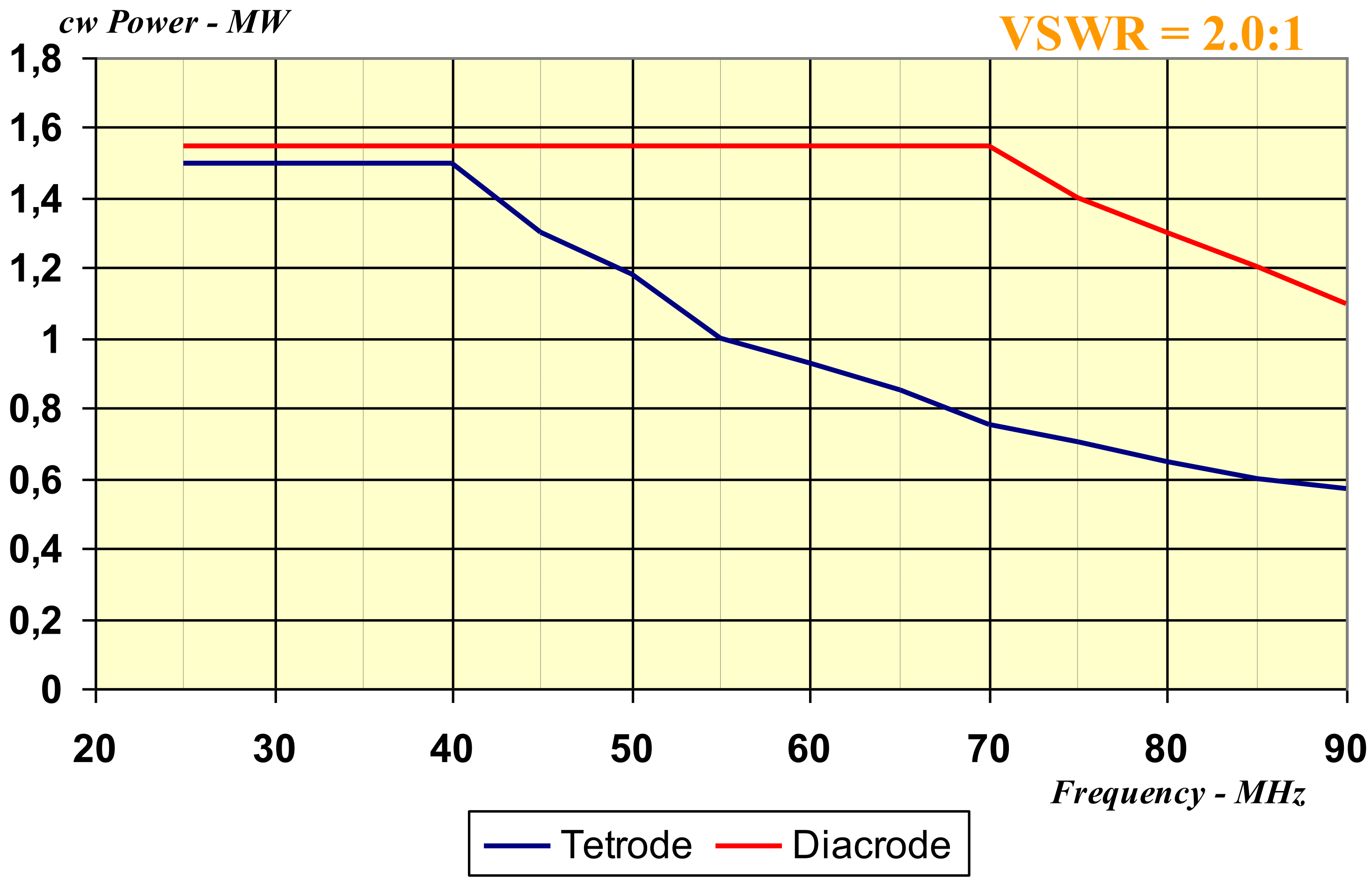


— Diacrode — Tetrode

TH526 Fusion Tetrode --> TH628 Fusion/Linac Diacrode

2 x f max and 2 x Pmax

TH628L Diacrode as a key component for fusion

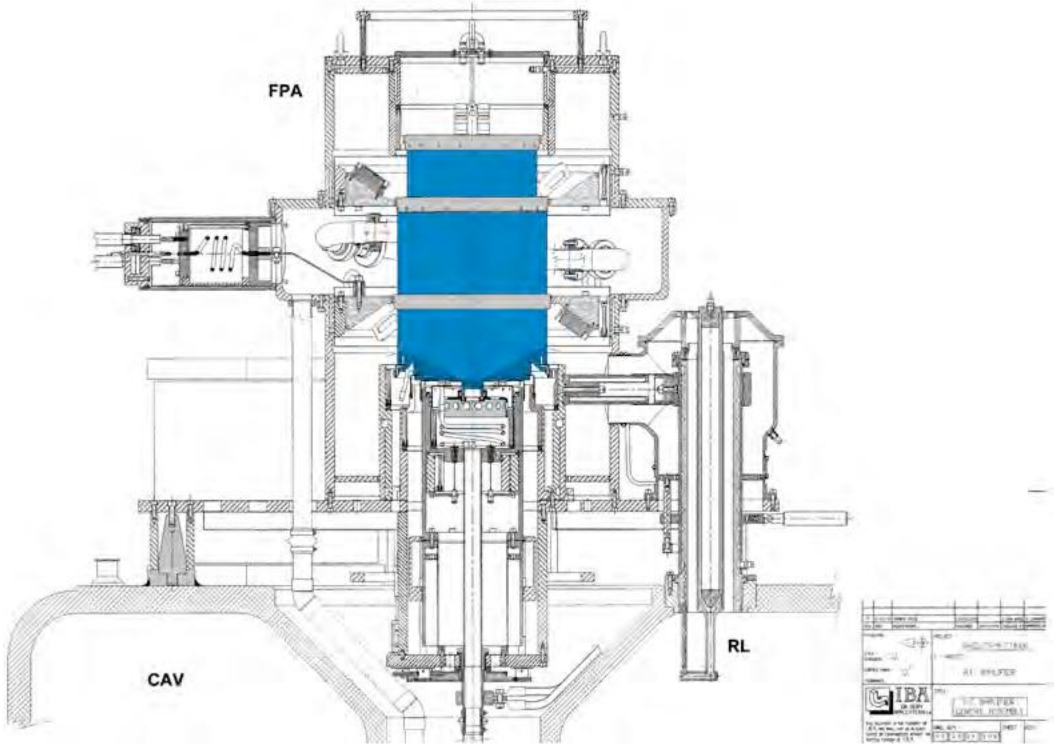


- Diacrode: 25 to 70 MHz, 1.5MW CW VSWR up to 2

Acceptance Test - First Production TH628 in Thonon, 1998

- **Met all LANL criteria, including 3 MW at 20%DF**

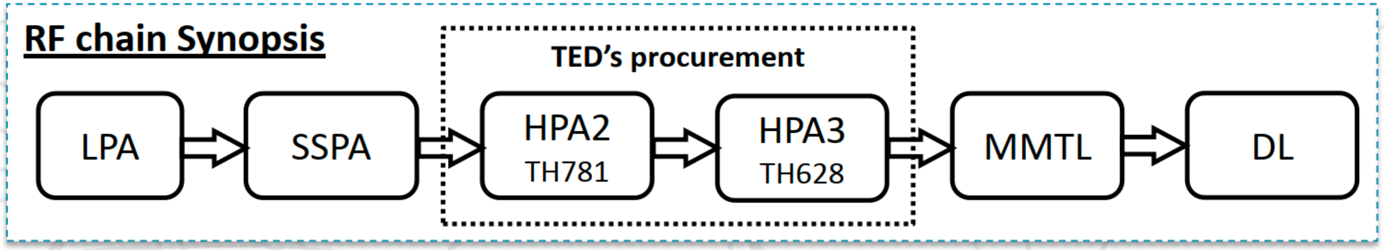
IBA Using TH628 at 1MW CW



- Rhodatron E-Beam machine for sterilization, industrial applications, at 107 MHz

THALES Activities for ICRH system

- The contract I-I/CON/003/TED/2012-13 between TED and ITER-India
  - Collaborative in nature and sharing responsibility for FAT & SAT by both the parties
  - Phase 1: Tube qualification phase using RF chain (half RF source) experimentation



Major specifications for the RF chain		
Amplification stage	HPA2	HPA3
Frequency range	35 – 65 MHz	
Forward RF power	120 kW @ VSWR ≤ 1.3	1700 kW @ VSWR ≤ 1.5
		1500 kW @ VSWR ≤ 2
Output bandwidth	≥ ± 1 MHz @ -1 dB	
Max. anode voltage	14.5 kV	27 kV
Overall efficiency	≥ 50 %	
Pulse length	CW	

Terminology:

LPA: *Low Power Amplifier*
SSPA: *Solid-State Power Amplifier*
HPA: *High Power Amplifier*
MMTL: *Mis-Matched Transmission Line*
DL: *Dummy Load*

Vacuum tube based amplifiers:

TH781: Tetrode
TH628: Diacrode

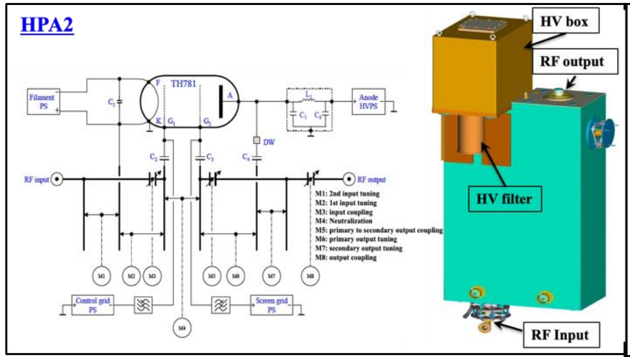
IBF/15 - March 25-27, 2015
Palais du Pharo / Marseille / France

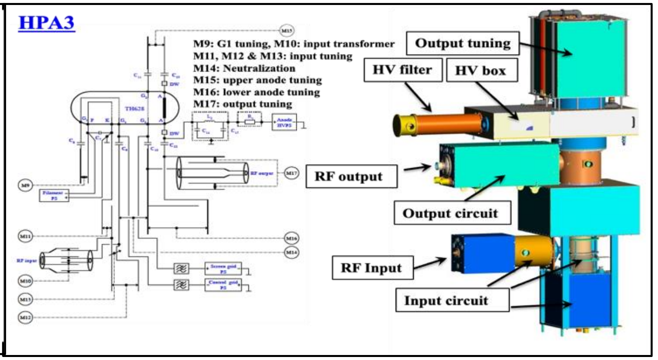
ITER RF Amplifier based on TH628L

Amplification: mW to MW → 90 dB gain

RF chain consists of:

- **Low power RF section (mW) + wide band pre-driver (10kW SSPA) + two tube based amplifiers: 130kW driver stage (HPA2) & 1.5 MW final stage (HPA3)**
- **Selected tubes:**
  - **for HPA2: Tetrode TH781**
  - **for HPA3: Diacrode TH628L**
- **Common grid configuration selected to provide stable operation**
- **Input & output cavities: tunable coaxial structures to provide impedance transformation for the required frequency range**
- **Coaxial structure provides**
  - low spurious
  - Low losses
  - natural EMI shielding

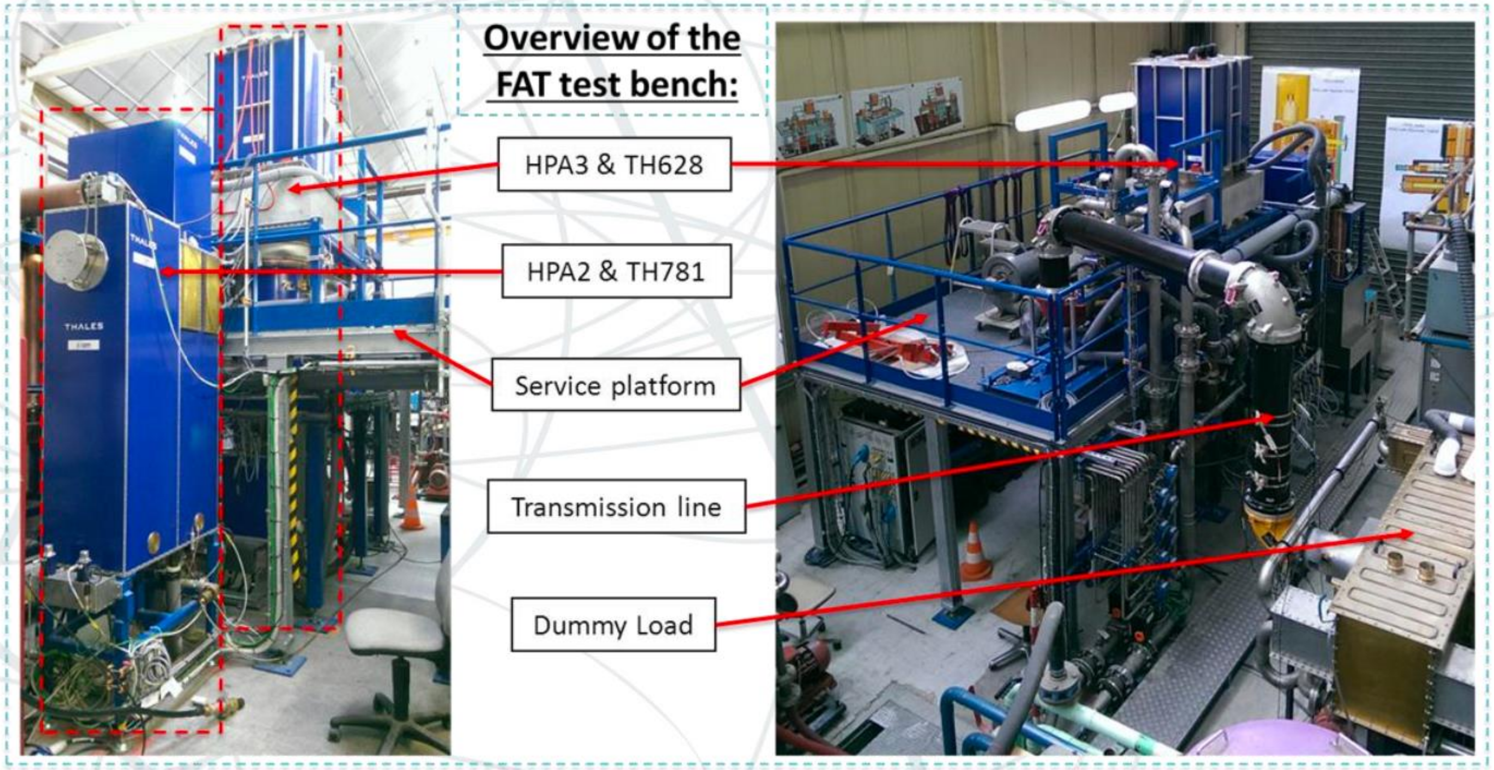




- **Since tubes can oscillate at higher order modes, damping material is used to suppress them**

ITER RF Amplifier based on TH628L

- **The Factory Acceptance Tests on matched load has been successfully performed**
- **The Site Acceptance Tests on mis-matched load (at ITER-India lab) in 2015**
  - 1.5 MW peak, 2000 s square pulse, up to 25% duty factor
  - 35 to 65 MHz, VSWR up to 2, any phase



Test results and tube parameters on HPA2 and HPA3

- A first R&D chain was developed using cascaded low power RF section (mW), wide band pre-driver (10kW SSPA) and two tube based amplifiers: 130kW driver stage (HPA2) & 1.5 MW final stage (HPA3).
- A diacrode was used for HPA3 stage

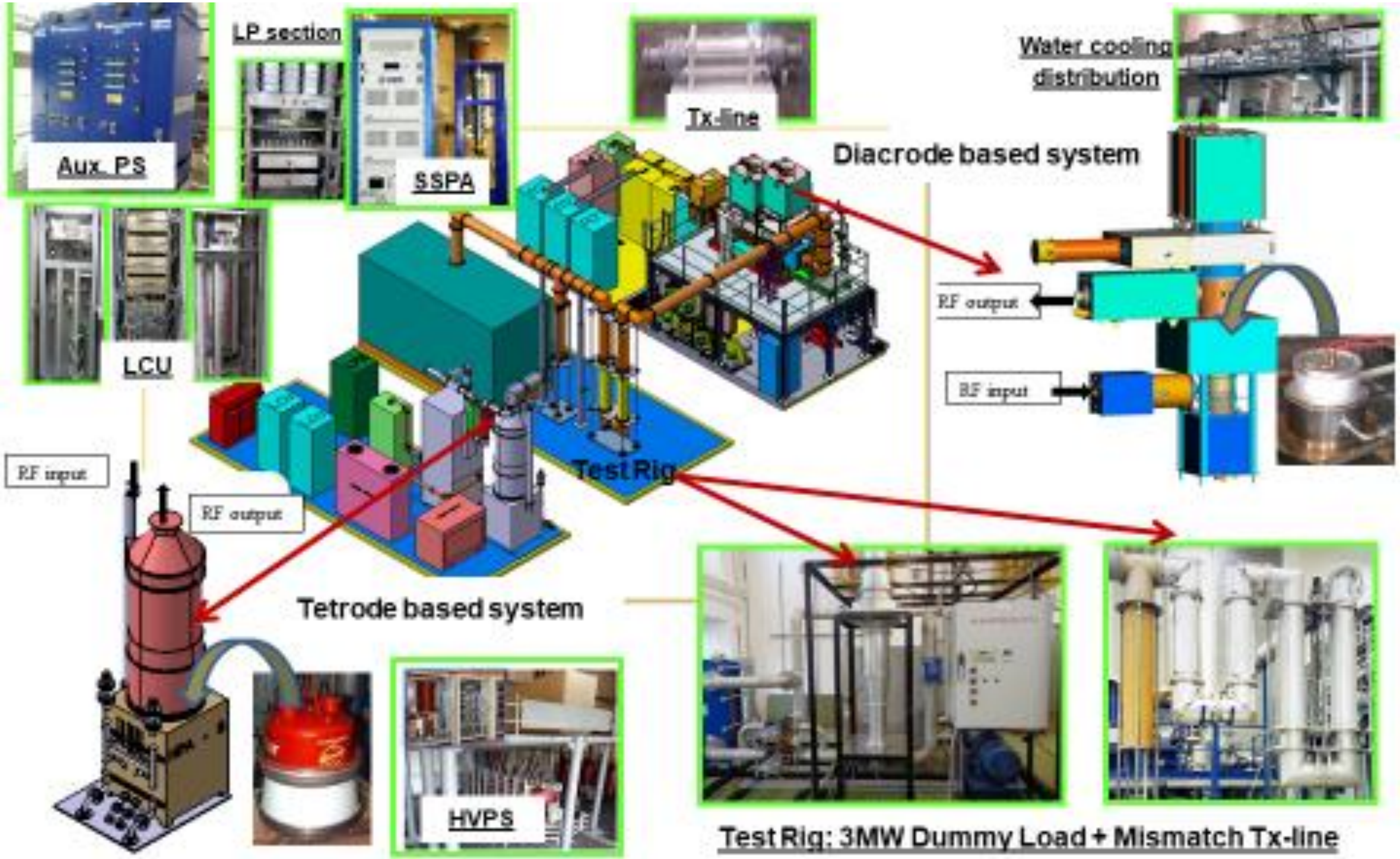
- R&D with Diacrode technology
  - for HPA2: Tetrode TH781 up to 130 kW
  - for HPA3: Diarode TH628L up to 1.5 MW

- To conclude on the test performed on the **tetrode+diacrode based system**, the **R&D requirements compliant with the ITER ones were fulfilled**

R&D Specification	Diacrode based system
1.5MW / 2000s / 35-65 MHz on matched load including 1dB BW test	Demonstrated at 36 MHz, 45 MHz, 55 MHz & 65 MHz
Design capability test at 1.7MW/3600s on matched load	Performed at 36 MHz
1.5MW/2000s at 65 MHz on mismatched load at 5 phase angles	Demonstrated at 0, 45, 90, 135 & 180 degrees
5 successive pulses at 1.5MW/2000s with 25% duty cycle at 65 MHz on matched & mismatched load	Demonstrated
Max. output harmonic level: < -20 dBc	Achieved
η ~ 50% - 60%	55% - 65%
Emergency power cut-off response: <10 micro sec	Achieved
RF exposure limit: < 1.0 mW/cm2	< 30 µW/cm2

Table 7: Demonstrated Capability of TH781+TH628 based amplifier chain

R&D program with two possible tube and cavity by INDA



ITER-RSZFNS v1.0
A.Mukherjee, FEC 2016

Schematic and picture views of R&D on tube and cavity facility in ITER India

Test results and tube parameters on HPA2 and HPA3

- The selected tubes for this second chain were the following
  - ✓ for HPA2: Tetrode 4CW150,000E (CPI, USA) up to 100 kW
  - ✓ for HPA3: Tetrode 4CM2500KG (CPI, USA) up to 1.5 MW

- The results obtained on the second chain based on CPI tube are listed in Table
- **All requirements were not fulfilled,** in particular the **bandwidth characteristics** (> 1dB) and the **output power** on the frequency range.
- **The upper frequency** for this system was found **55MHz**

R&D Specification	Tetrode based system
1.5MW / 2000s / 35MHz & 65MHz on matched load	Demonstrated at 36 & 55MHz
BW:±1MHz at 1dB	Partially complied
Design capability test at 1.7MW/3600s at 36 MHz on matched load	Performed at 36 MHz
1.5MW/2000s at 65 MHz on mismatched load at 5 phase angles	Demonstrated only at 55MHz
5 successive pulses at 1.5MW/2000s with 25% duty cycle at 65 MHz on matched & mismatched load	Demonstrated only at 55MHz
Max. output harmonic level: < -20 dBc	Achieved
η ~ 50% - 60%	55% - 70%
Emergency power cut-off response: <10 micro sec	Achieved
RF exposure limit: < 1.0 mW/cm2	< 100 µW/cm2

Table 10: Results obtained on the chain based on full tetrode technology chain

Contents

Transmission Line Heat Loads in ITER

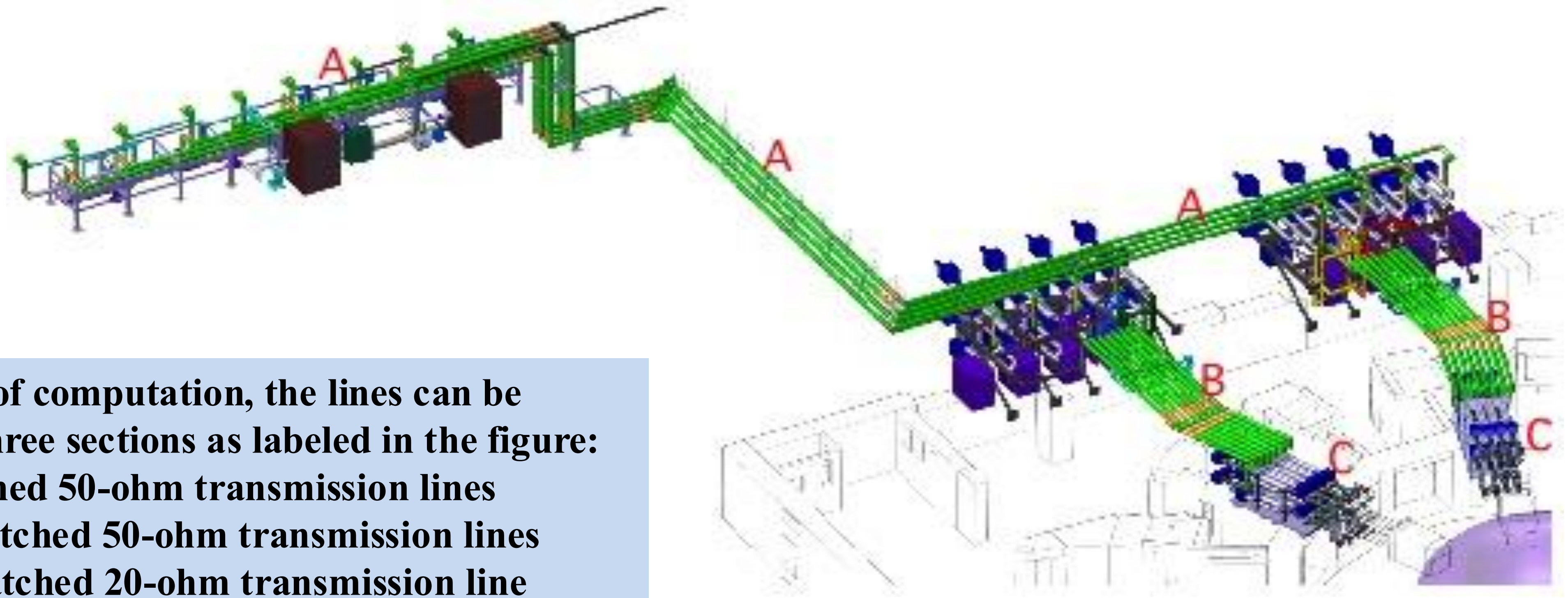
- **The finite resistance of the coaxial transmission lines will cause heating of the inner and outer conductors when RF power is passed through the coax.**

- **The heat will have to be removed from the conductors to keep them from getting too hot.**

ITER_D_JH8R2D v1.1

ICH Transmission Line Heat Loads in ITER

- RF power flows from RF sources through 50-ohm matched transmission lines (A) to the matching system.
- Then through unmatched 50-ohm transmission line (B) from the matching system to the prematching system. Then from there to the antenna



- For purposes of computation, the lines can be divided into three sections as labeled in the figure:
  - A – matched 50-ohm transmission lines
  - B – unmatched 50-ohm transmission lines
  - C – unmatched 20-ohm transmission line

ITER_D_JH8R2D _L8BGFY_v1_0, ITER_JH8R2D_v1_1, ITER_9YPU4V_v1_1

3D picture of the ICH system

ICH Transmission Line Heat Loads

Table 1. Average Power Loss/m for initial power operation, f = 55MHz.

	Section A		*Section B*	*Sec. C1*	*Sec. C2*
Zline (ohms)	50	50	50	20	20
OD (mm)	302	302	302	330	230
Avg. T_{inner} (C)	100	100	100	60	60
Avg. T_{outer} (C)	60	60	60	60	60
RF power (MW)	2.5	3	1.5	1.5	1.5
Max voltage (kV)	22.4	21.2	30	45	45
VSWR	2	1.5	6	34	34
P'in (kW/m)	0.360	0.375	0.535	3.804	5.458
P'out (kW/m)	0.214	0.223	0.317	3.975	5.704
P'tot (kW/m)	0.574	0.598	0.852	7.779	11.162

How much power will be lost in the inner and outer conductors

Table 2. Transmission line losses for one antenna for initial power.

Section	*Line length(m)*	*Power per line (kW)*	*No. of lines*	*Total power (kW)*
A	104	62.2	4	249
B	36	30.7	8	245
C1	7	54.5	8	436
C2	4	44.6	8	357
Total				**1287**

How will the inner and outer conductors be cooled

Table 9. Comparison of losses with Al and Cu outer conductors

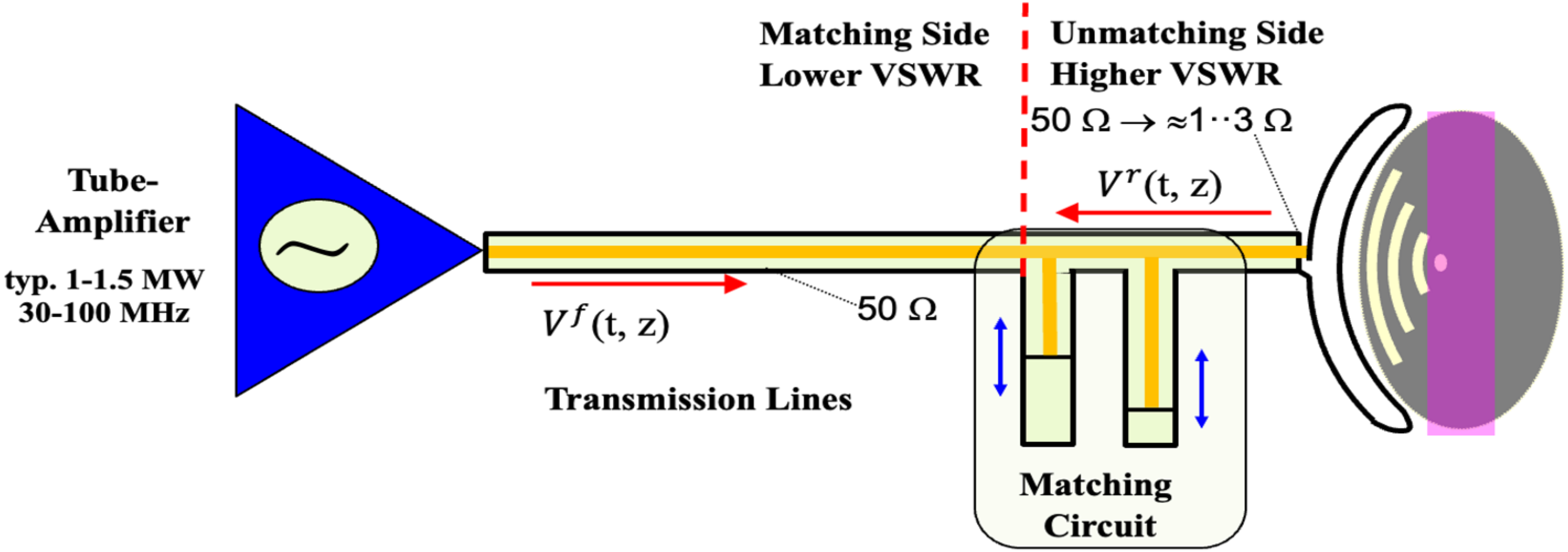
Section	*Al outer (kW)*	*Fraction of source pwr.*	*Cu outer (kW)*	*Fraction of source pwr.*	*Difference (kW)*	*Fraction of source pwr.*
A	249	2.1%	220	1.8%	29	0.24%
B	245	2.0%	217	1.8%	28	0.24%
C1	436	3.6%	366	3.0%	70	0.58%
C2	357	3.0%	300	2.5%	57	0.48%
Total	**1287**	**10.7%**	**1102**	**9.2%**	**185**	**1.54%**

- Preliminary calculations indicate that approximately **800 kW of additional power** could be dissipated in the **matching system** components, giving **total losses from the RF sources to the antenna of up to 2200 kW** using the present baseline design with hybrid phaseshifters in the prematching and matching systems
- **ITER design: Section A-Gas cooling; Section B and C –Water cooling**

Contents

Antenna Coupling to plasma and link with wave reflection

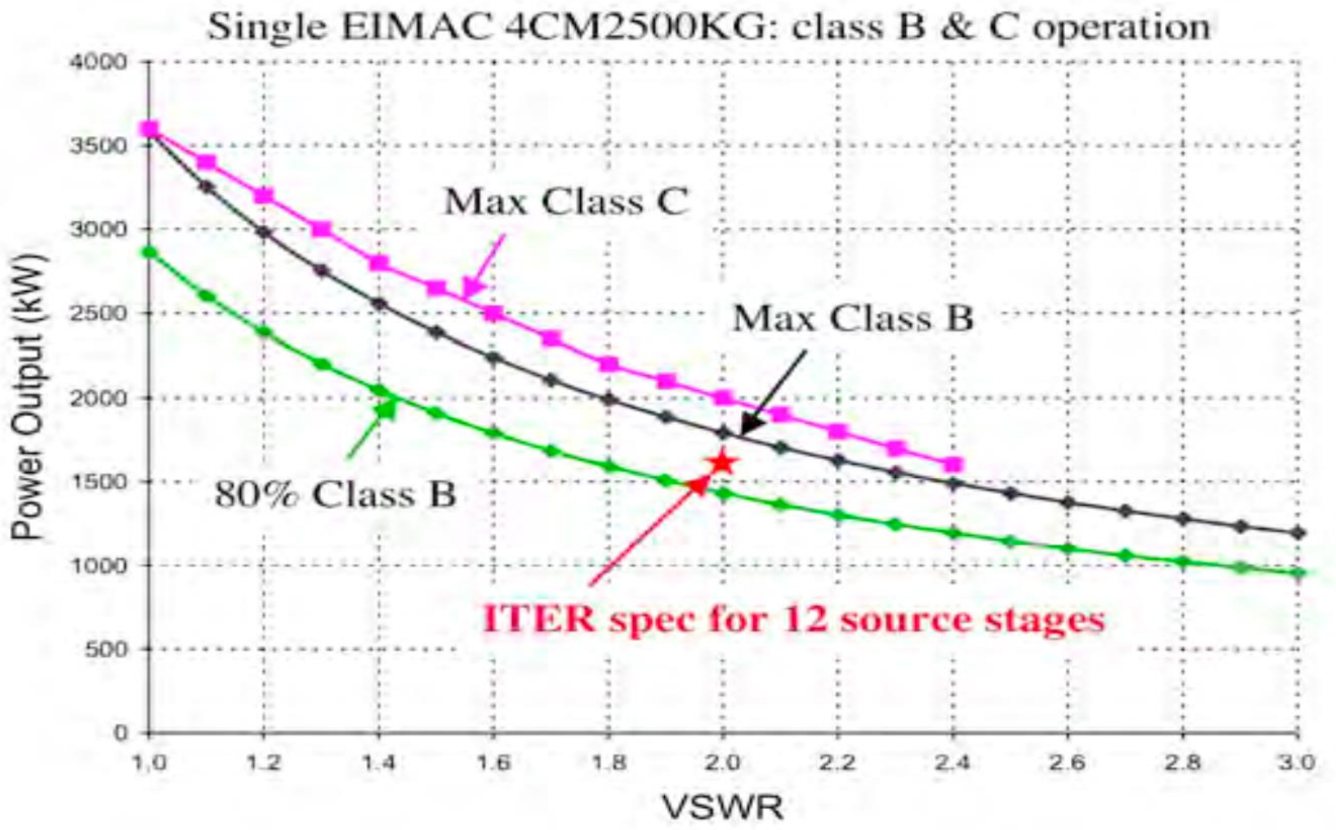
- **Transmission line (Z_0) terminated by antenna(load impedance Z_A)**
  - ✓ If $Z_0 = Z_A$, All power transmitted to the load. No power reflected
  - ✓ If $Z_0 \neq Z_A$, Not all power transmitted. Some power reflected
- **Matching system using mechanical adapting systems modified between shots or in real time to cancel reflected power**



Matching Systems on major devices in the world

	Frequency range (MHz)	Installed generator power	Matching system	System response
ASDEX Upgrade	30–120 (30–60 used)	4 × 2 MW	Double stub Hybrid coupler	Between shots Fixed
C-Mod	80 40–80	2 × 2 MW 4 MW	Trombone Stub	Between shots Between shots
D-III-D	60 60–120	2 MW 1 MW at 120 MHZ	Hybrid couplers	Fixed
JET [8]	23–57	16 × 2 MW	Trombone Stub Frequency	16.5 cm/s 5 cm/s ±200 kHz in 1 ms
JT-60 U	102–131 (112)	8 × 1.5 MW	Trombone Stub Frequency	0.5 cm/s 2 cm/s 400 kHz 10–80 ms
NSTX [54]	30	6 × 2 MW	Trombone Stub	Between shots Between shots
TEXTOR	25–38	2 × 2 MW	Stub Trombone Capacitors	Between shots Between shots 20–30 ms
Tore Supra	35–80	3 × 2 × 2 MW	Resonant double loop (capacitors)	200 ms

Antenna Matching



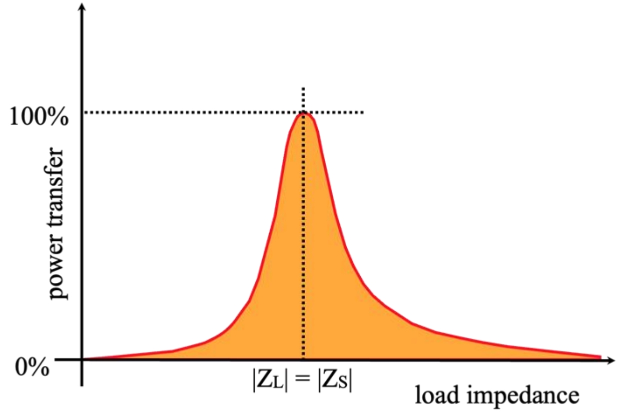
- *The transmitter cannot be connected to the antenna directly because of impedance mismatch.*
- *A matching network has to be used to transform the antenna loading to 50 ohm*
- *Their location close to the antenna minimises losses..*

- **The transmitter max power output is reduced at higher VSWR.**
- **At ITER spec, VSWR = 2 → P_{refl}/P_{forw} = 1/9.**
- **In EAST, we normally set the threshold close to VSWR ~ 3.**

Y.Lin 2008 Summer school

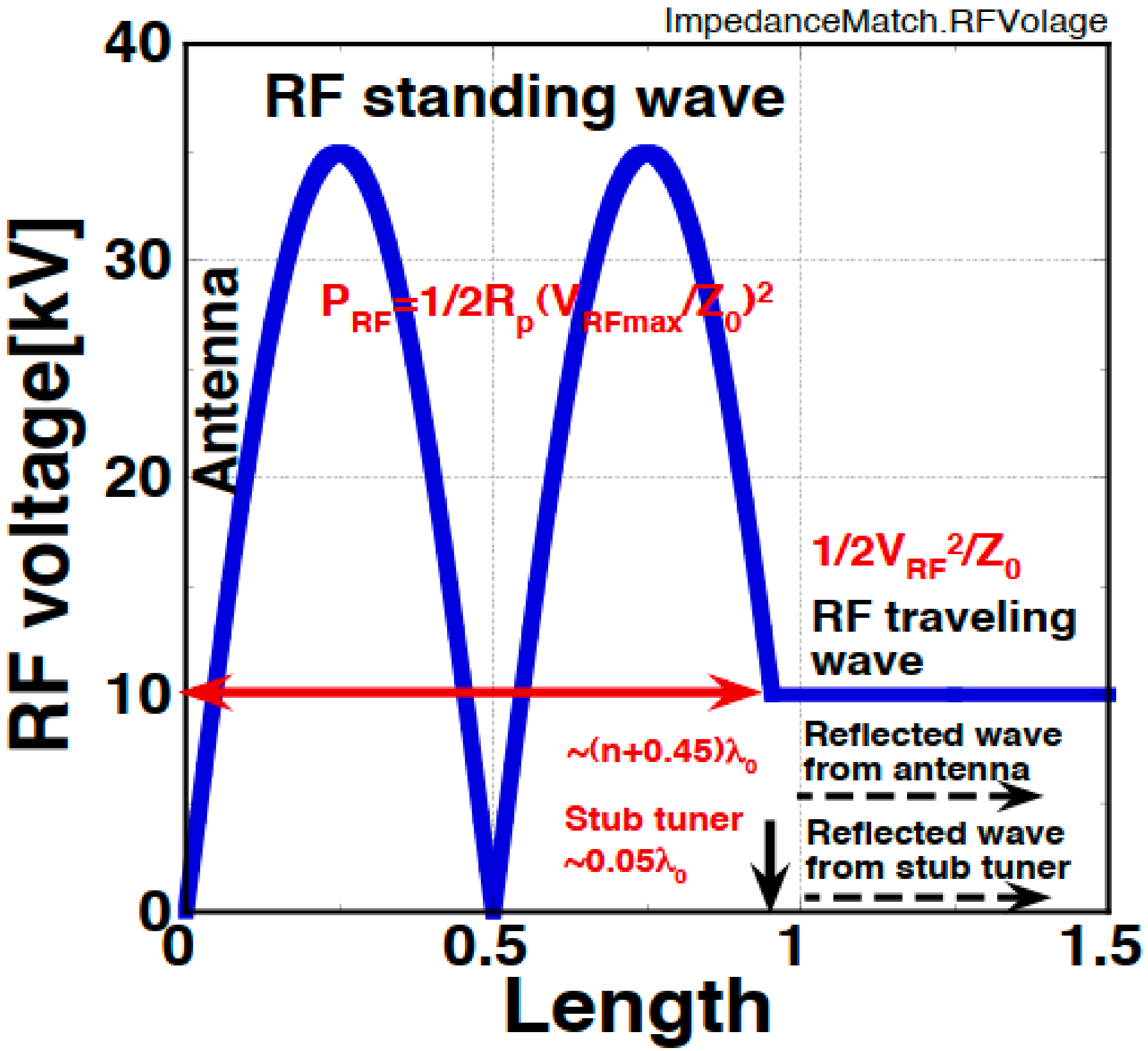
Principle of Antenna Matching

- **Matching objectives:**
  - ✓ **Maximize delivered power and reduce feeder loss**
  - ✓ **Control array-current phase and amplitude to create the required spectrum**
  - ✓ **Keep generator-side reflection below the trip threshold**
- **Classical matching uses a tunable resonant network to transform complex antenna impedance to the real source impedance**
  - ✓ Reactive components such as capacitors or shunt short-circuited line sections called stubs;
  - ✓ Phase shifters or line stretchers.
  - ✓ Classical tuning serves steady state. load changes require retuning.
- **Conjugate-T / hybrid schemes handle fast ELM loads**

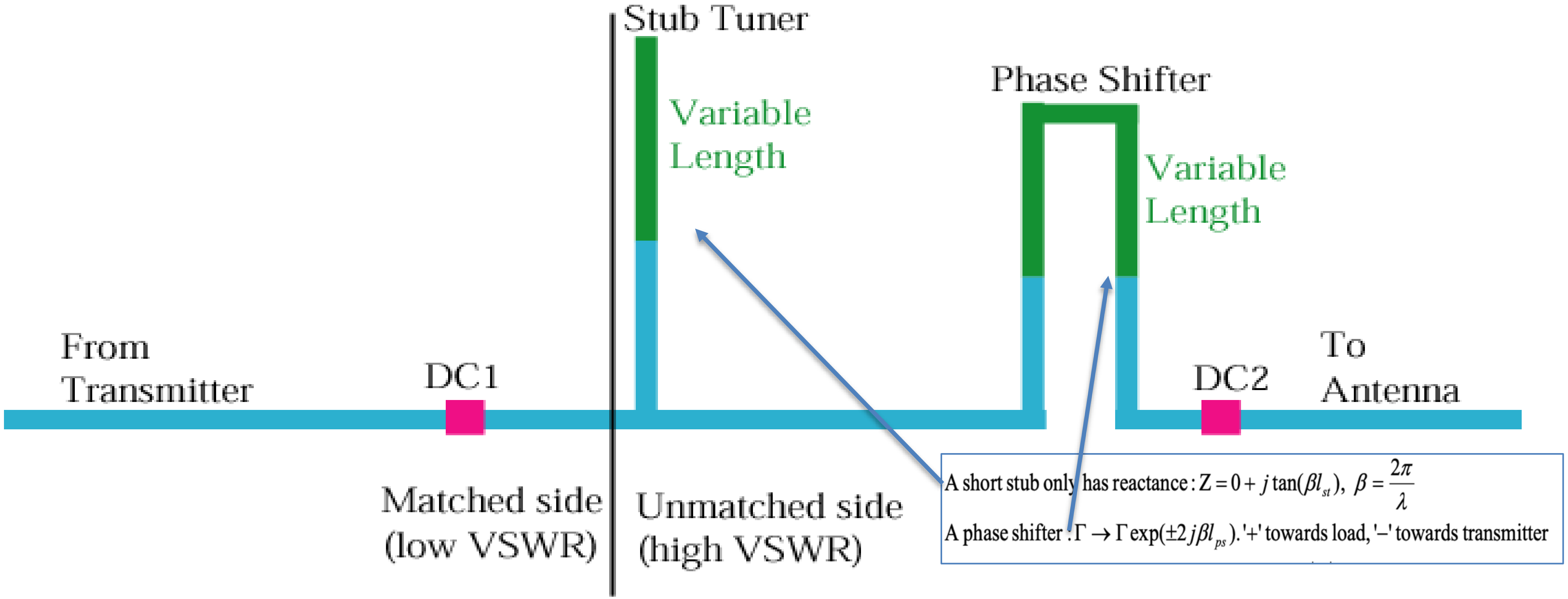


Principle of Impedance Matching

- In the right figure a standing RF wave is excited between antenna and a stub tuner
- P_{RFA}:RF power between antenna and a stub tuner $P_{RFA}=1/2R_p(V_{RFS}/Z0)^2$, $R_p<<Z0$
- P_{RFS}:RF power between stub tuner and RF generator $P_{RFS}=1/2V_{RF}^2/Z0$
- $P_{RFA}=P_{RFS}$, Then the length of stub tuner is determined taking into account the phase of reflected RF wave at the stub tuner junction.



Stub Tuner/Phase Shifter System



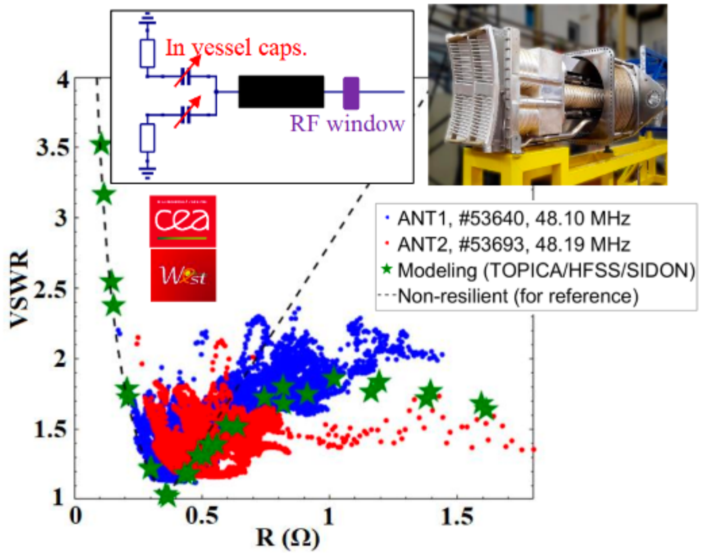
- **Goal: zero reflection on the matched side at all time.**
- **Stub tuner and phase shifter are adjusted between-shot based on anticipated average antenna loading.**
  - → **Difficult maintaining the match when the antenna loading changes significantly during a discharge.**
  - → **Difficult finding ideal ST/PS positions in experiments with large plasma parameter variation shot-by-shot (e.g., density scan) .**

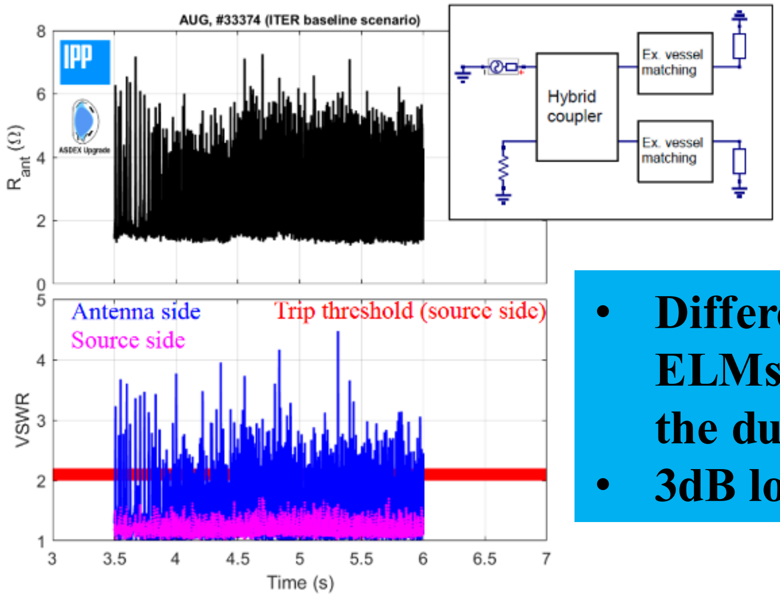
Real-time Matching Techniques

- **Frequency modulation: Varying RF source frequency to change impedance**
  - Fast (milliseconds)
  - Requires a long transmission line and a wide-band response of the transmitters
  - Tested on JET and LHD
- **Dielectric liquid: Pumping/filling dielectric liquid in stubs and/or phase shifters to change electrical length**
  - Slow (seconds), but good for long pulse operation
  - Installed on LHD
- **Ferrite material: Varying magnetic field on ferrite material to change effective electrical length**
  - Fast (milliseconds)
  - Limited range of electrical length variation
  - Tested on ASDEX-Upgrade (Successfully implemented on Alcator C-Mod)

ELM-tolerant behavior

- **Sensitive impedance matching + harsh non-stationary plasma loading. Need for:**
  - Reconfigurable matching circuit (+ need to cover wide band, 40-55 MHz for ITER ICRF).
  - Real-time controlled matching. But electromechanical tuning elements cannot cope with **very fast (< 1ms) plasma loading variations** (×2 - ×5, or more).
  - Load-resilience (ex: Internal Conjugate-T, External Conjugate-T, 3dB splitters, etc.)





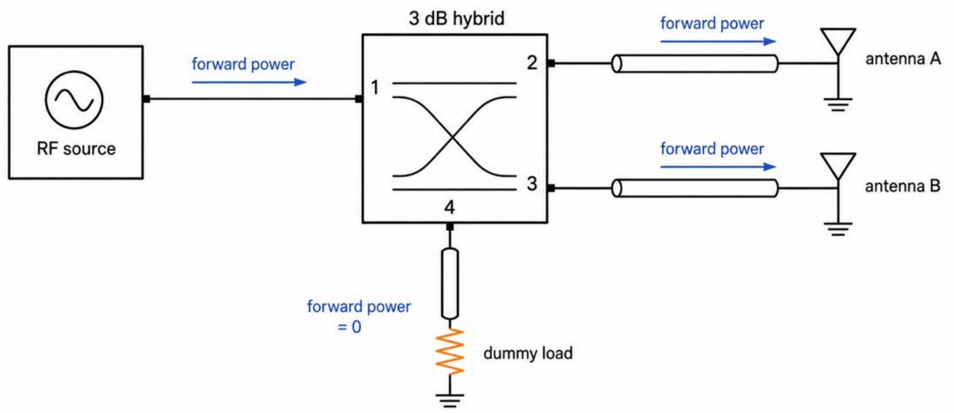
- **Differences in the RF power management during ELMs (delivery to plasma vs diverted delivery to the dummy-load)**
- **3dB load-resilient system is the baseline for ITER**

W. Helou, CWRF2022

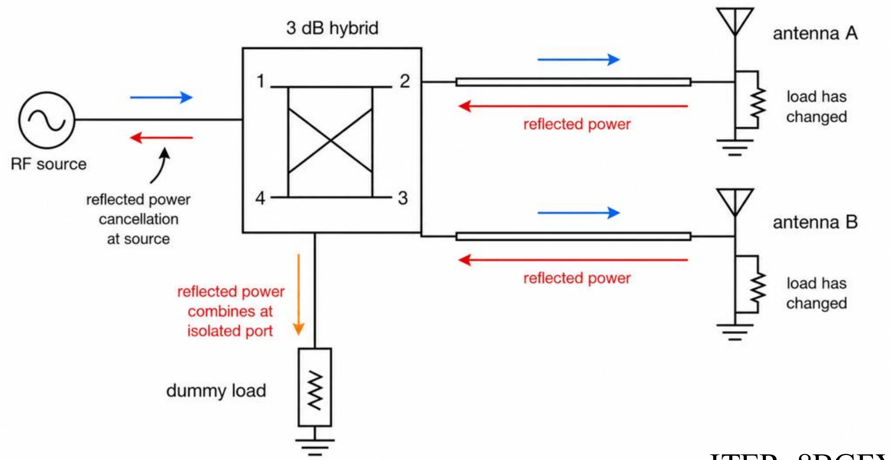
ELM-tolerant behavior

- **Under normal operation, system is matched**
  - Source power all goes to antenna
- **Elms can cause system to be *unmatched***
  - Some power reflected back toward hybrid splitter
- ***With proper design*, reflected power goes to load, not back toward source**

System matched



System unmatched

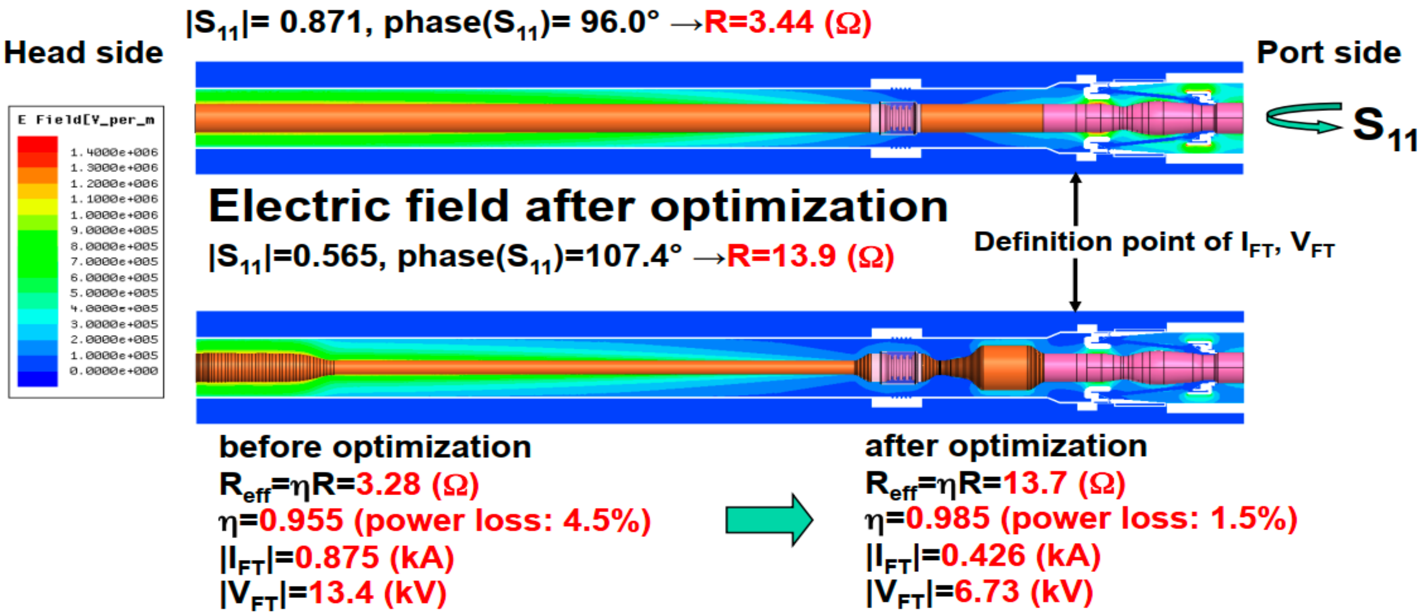


ITER_8BGFY_v1_0

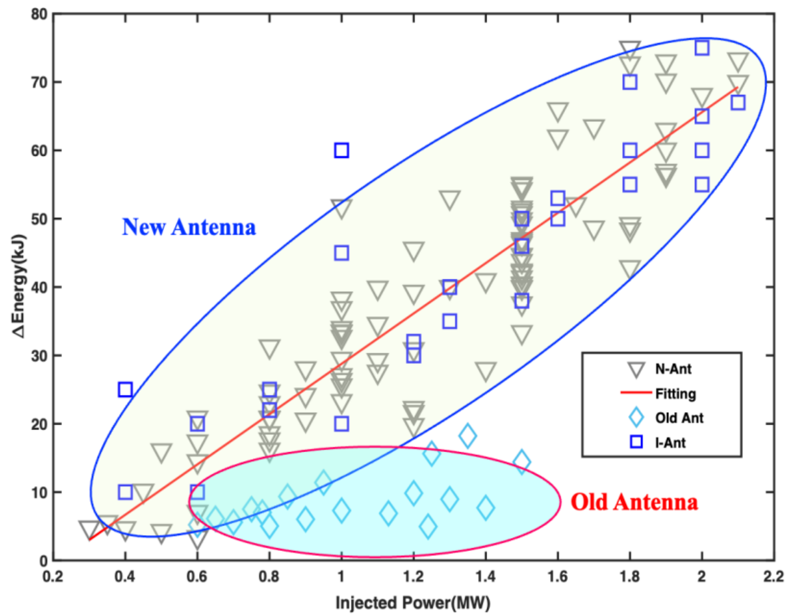
Contents

CW high power Antenna Design

- **In antenna design phase:**
  - Straps optimization to R ↗ (& R/X² ↗)
  - Optimize antenna feeding circuit →V ↘, I ↘ & P ↗
- **With varied characteristic impedance, Z_c along co-axial line from antenna to ceramic feed-through**
- **The loading Resistance can be increased 3 times in optimized selection of Z_c**



Optimization of characteristic impedance of antenna feeding line at LHD

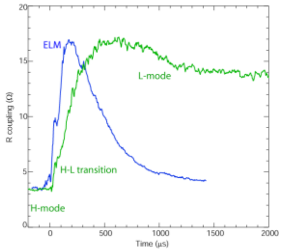


Antennas and feeding line optimization at EAST

IC antennas near the plasma edge lack credible solutions

Multiphysics Constraints →High Power Steady State Operation becomes challenging

- **Challenge: CW (10^3 s) high RF power (10^7 W) →High Power density and voltages**
  - ✓ Large RF voltages (10^4 V) & large RF currents (10^3 A)&Large E-fields (10^6 V/m)
  - ✓ CW metal loss (10^4-10^6 W/m^2) & and CW dielectric loss (10^6 W/m^3, RF windows' ceramics)
- **Challenge: Maintain Reliable Power Transfer**
  - Transient phenomena modify the coupling on fast time scales→ Very large uncertainties on loading



- **Challenge: Impurities**
  - High Z metallic materials are favored for PFCs → Impurity sources and contamination are more difficult to manage →Plasma tolerance of high Z materials is much lower
- **Challenge: Survivability is a major issue because of the harsh environment**
  - RF Enhanced Heat Flux &PMI → Exceeding the power handling capability of the antenna and other PFCs.
  - Energetic particles either ions or electrons from the plasma or from RF local fields can significantly limit antenna lifetime

💥 **Balance siting antennas near enough to plasma for antenna loading but sufficiently far to minimize impurities and PMI issues. → Lack low field side solution**

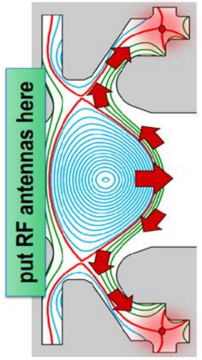
💥 **New devices would have freedom to find different engineering design solution**

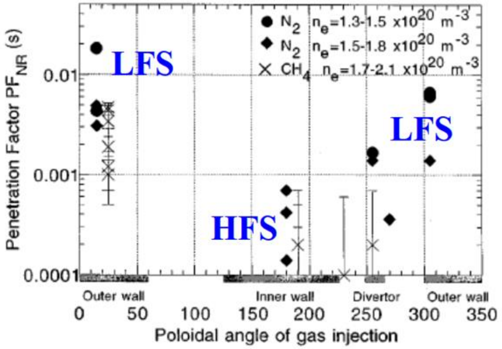
S.J. Wukitch TOFE 2014

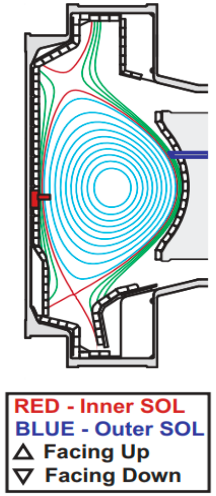
New Innovation: High Field Side RF Launch

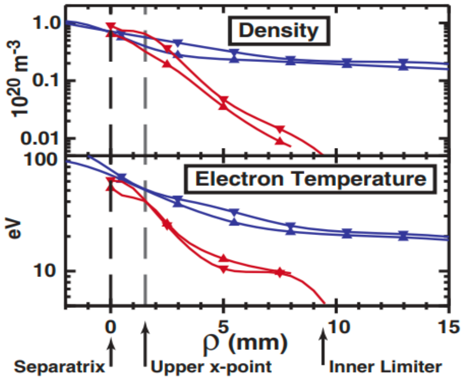
Increased Engineering Complexity has Potential for Significant Benefits

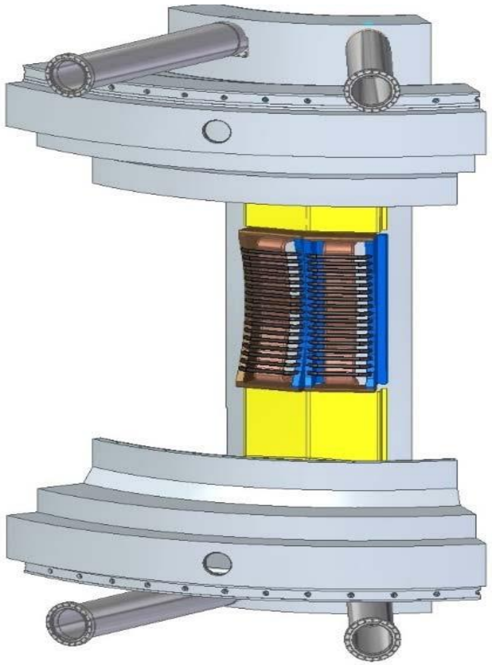
- **Robust coupling.**
  - Quiescent high field side SOL - no ELMs or load variations from density perturbations.
  - Distance to last closed flux surface is significantly reduced from 10s of cm to few cm.
  - Density control through magnetic geometry.
- **Reduced erosion, impurity source and contamination.**
  - Reduced erosion, sputtering, and RF enhanced convection
  - 10x better impurity screening
  - Safe haven from energetic ions/electrons.











Wukitch_SOFE-2015

Summary

- **Enormous progress in understanding ICRF Technology in fusion devices has been made in the last 70 years**
  - Efficient RF sources, low loss transmission lines and robust antennas
  - Innovative technology development played a key role

- **ICRF Heating Proven, but Integration Challenge Remains**
  - Much more needs to be done in this area for reliable and robust performance
  - Important applications still need to be resolved

- **ICRF Systems will certainly play an important role in Next Step devices**
  - An exciting future: Integration of RF physics and technology in ITER, BEST, SPARC, DTT, etc.

Acknowledgements

- This lecture is prepared solely for educational purposes. The material is based primarily on publicly available presentations, publications, textbooks, and technical documents produced by experts in fusion and RF heating worldwide. The content has been selected, synthesized, and reorganized by the lecturer for teaching purposes.
- I would like to express my sincere appreciation to all the researchers, engineers, and experts whose work, presentations, and technical insights have contributed to this lecture. Their valuable contributions have greatly supported the preparation of these teaching materials.
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Thank you !