IC Power Source System for ITER – Indian In-kind Contribution

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On behalf of ITER-India

6th ITER International School.
Ahmedabad, India, 02-06 Dec 2012

Outline

IC H&CD System for ITER

- Functional Requirements & Layout
- Main Features & sub-systems

IC Power Source System

- Scope & Deliverables
- Functional specifications & Design consideration
- Technical Challenges involved
- R&D Activity
- Test facility

IC H & CD System for ITER

Functional Requirements

- ITER require 20MW of ICRF power to a variety of ITER plasmas (with emphasis on D-T operation), in quasi-CW operation (pulses up to 3600 s with 25% duty cycle)
- It covers a broad range of magnetic field operation
- Major requirements are for heating plasmas & driving plasma current
- It will perform IC wall conditioning at low power between main plasma shots
- System will be resilient to rapid antenna loading variations (L→H transitions, ELMs)

ITER IC H&CD Scenarios

Resonance	MHz	Comments
$2\Omega_T=\Omega_{3He}$	53	Second harmonic tritium + minority heating of ^{3}He to optimize ion heating (Nominal B_T= 5.3T)
FWCD	55	On axis current drive (Nominal B_T= 5.3T)
Ω_{3He}	45	Minority ion current drive at sawtooth inversion radius (outboard) (Nominal B_T= 5.3T)
Ω_{3He}	40 - 55	Minority heating of ^{3}He in H, D, ^{4}He or DT (B_T= 3.7 to 5.3T)
Ω_H	40 - 55	Minority heating of H in D, He or DT at reduced magnetic field (2.5 to 3.8T)

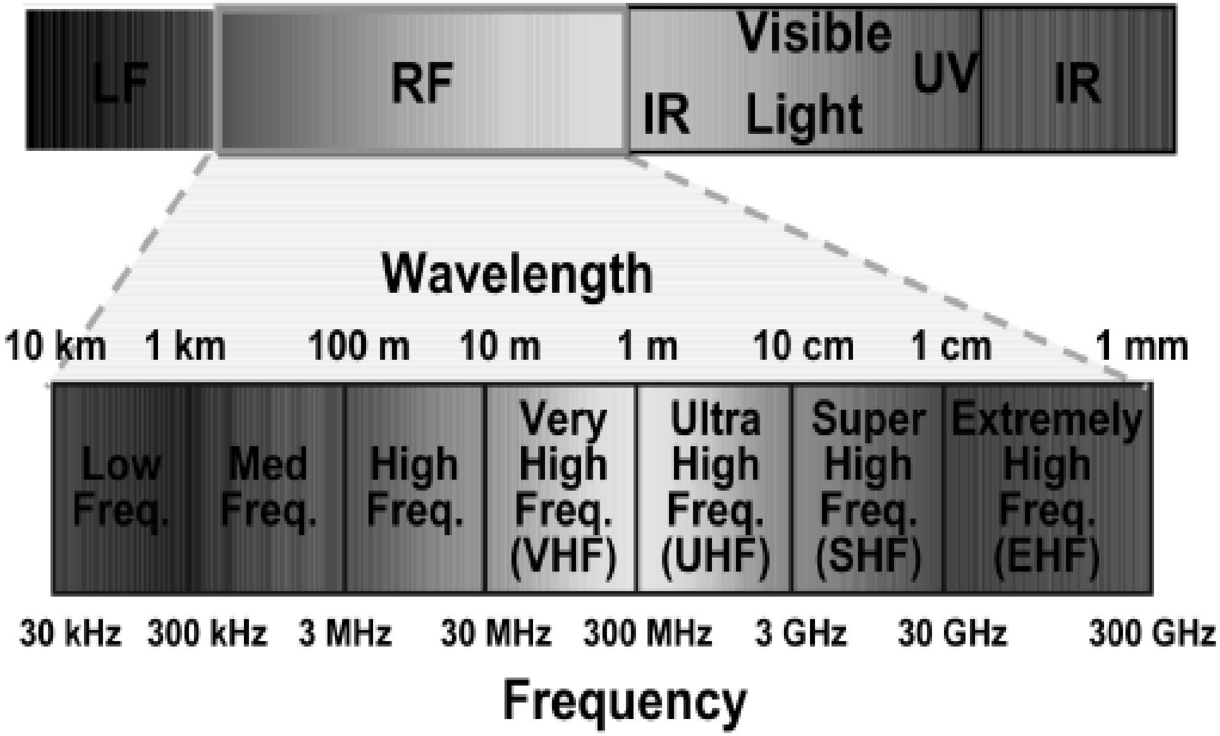
'Progress in the ITER Physics Basis',

Nucl. Fusion 47 6, June 2007

Freq. for RF Source: 35-65 MHz

In which range ICRF falls

Radio Frequency ranges from 30 kHz to 300 GHz

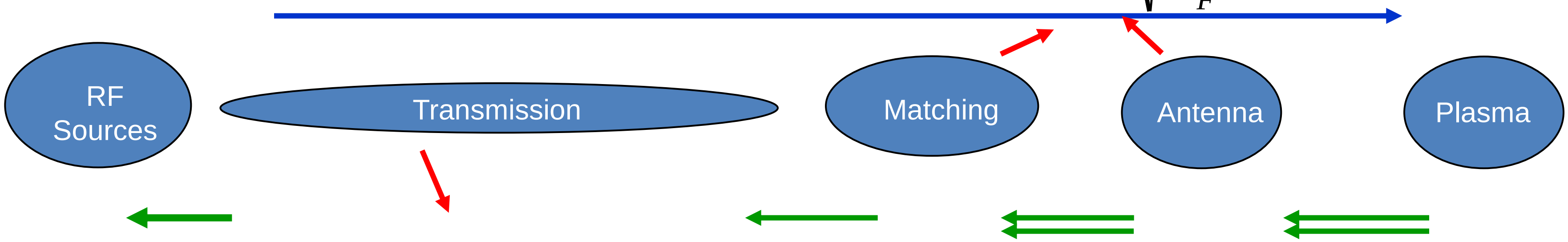


ICRF falls in VHF band

RF power to antenna via Tx-line & Matching

VSWR (Voltage Standing Wave Ratio):

$$\frac{1+\sqrt{\frac{P_R}{P_F}}}{1-\sqrt{\frac{P_R}{P_F}}}$$



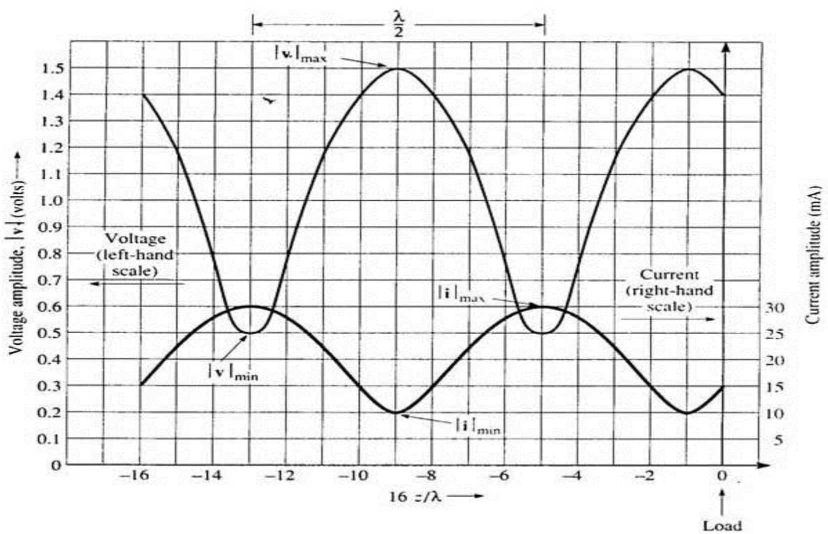
RF losses

Reflected power P_R

Forward Power P_F

ρ (reflection coefficient) = Vr/Vf or Ir/If

VSWR = (1 + ρ)/ (1 - ρ)



Special Cases to Remember

A: Terminated in Zo

$$\rho = \frac{Zo - Zo}{Zo + Zo} = 0$$

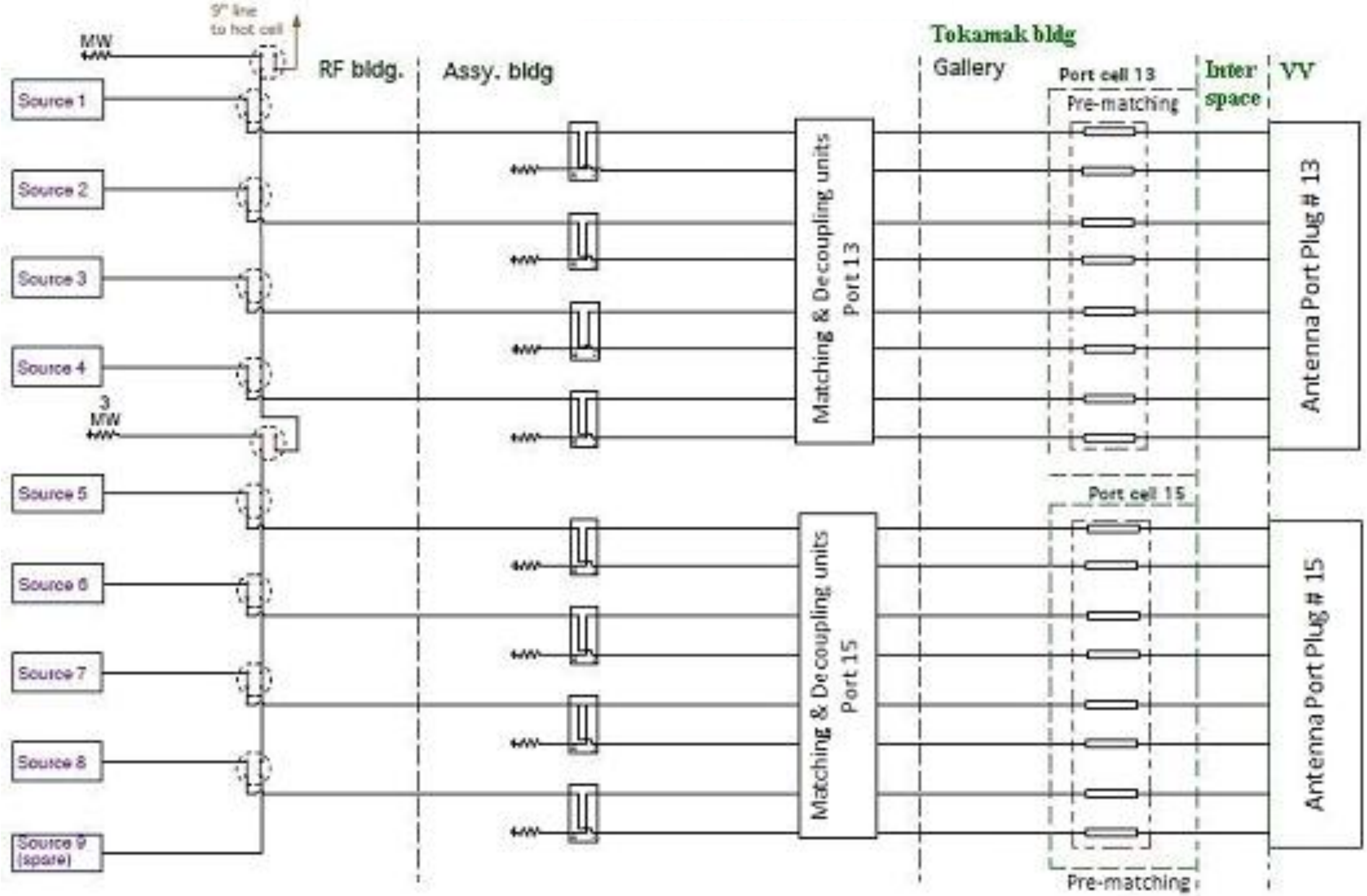
B: Short Circuit

$$\rho = \frac{0 - Zo}{0 + Zo} = -1$$

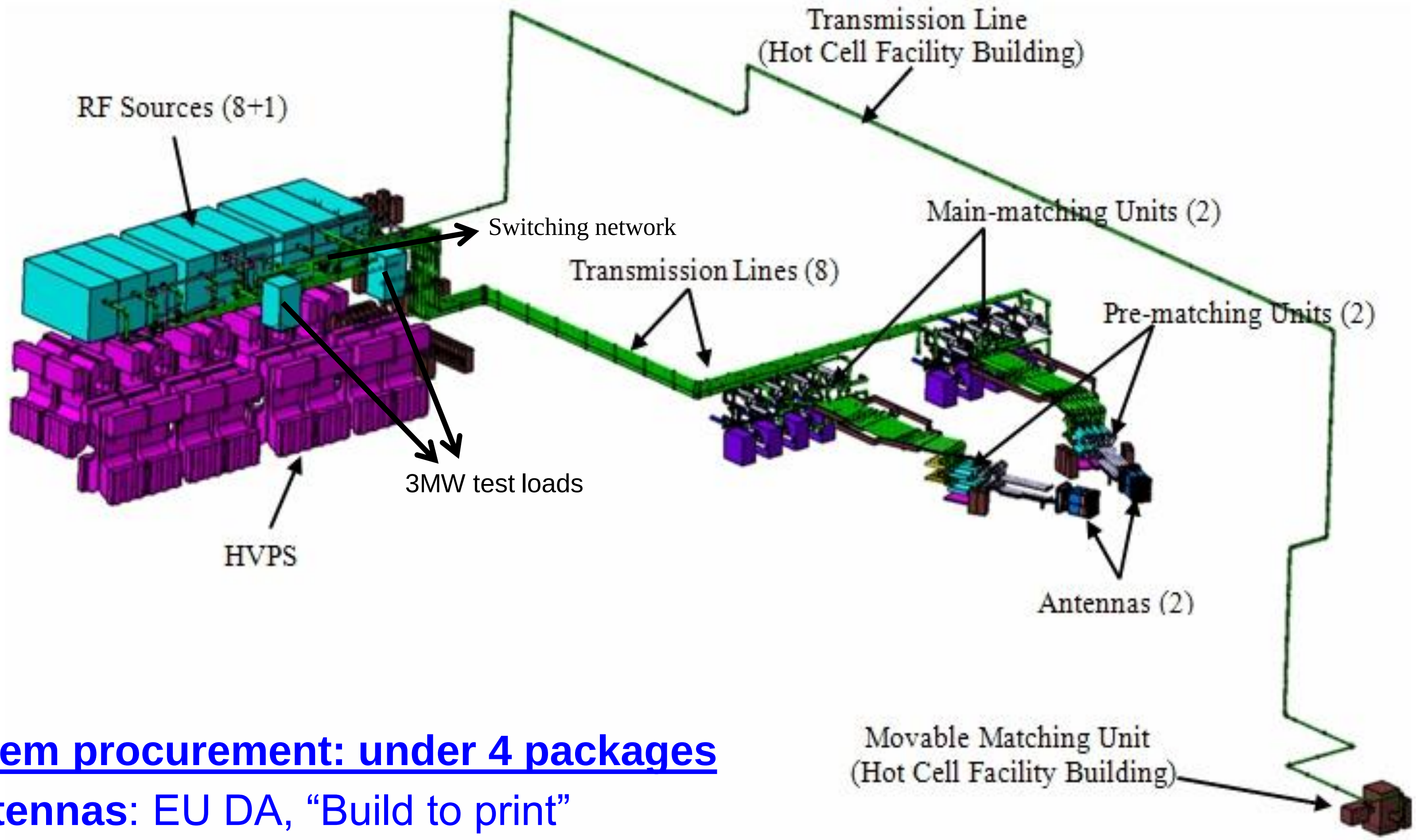
C: Open Circuit

$$\rho = \frac{\infty - Zo}{\infty + Zo} = 1$$

Line diagram of IC system



Layout of IC system



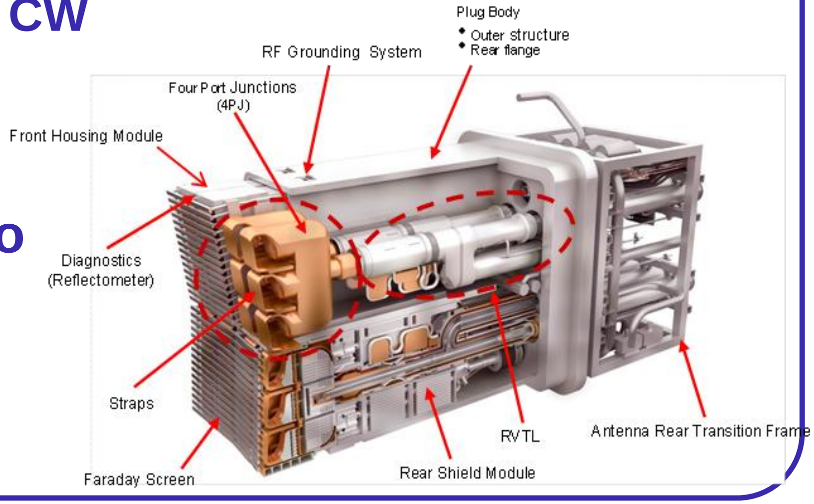
System procurement: under 4 packages

- **Antennas**: EU DA, "Build to print"
- **Transmission lines and matching systems**: US DA, Functional Specifications.
- **RF sources:** IN DA, Functional Specifications
- **HV Power Supplies**: IN DA, Functional Specifications, + IO (part of HVPS).

Main Features of ITER IC H&CD System

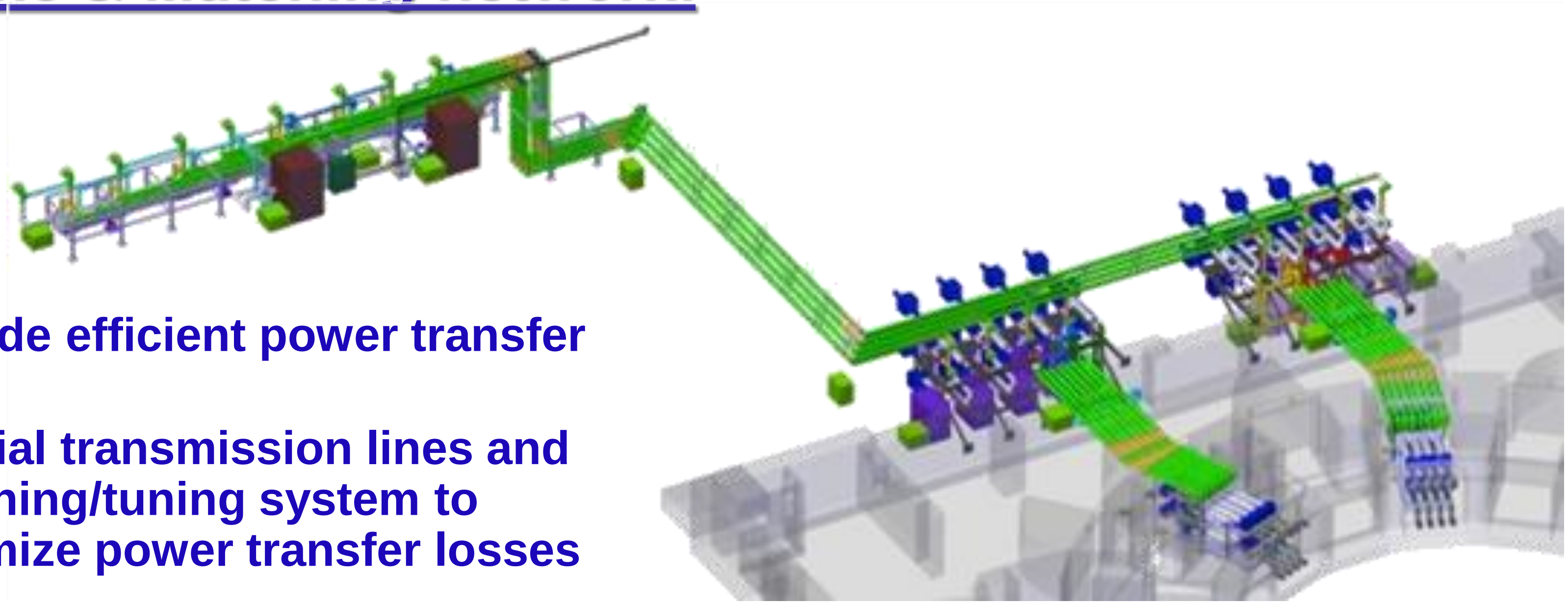
Antenna Port Plug:

- Broadband (40-55MHz) antenna arrays will be installed in 2 equatorial ports (#13 & #15) having 20 MW capability
- Having two antennas
  - strongly reduces risks associated with
    - Very large uncertainties on the edge density profiles, hence on antenna coupling to the plasma
    - RF voltage stand-off (reduced risk of arcing)
    - RF current (i.e. dissipation) limit in CW
  - Allows dual frequency operation
  - Possibility of future up-gradation to 40 MW



Main Features of ITER IC H&CD System

Tx-line & Matching network:



- **Provide efficient power transfer**
- **Coaxial transmission lines and matching/tuning system to minimize power transfer losses**
- **Pressurized lines transmit up to 6 MWs per line**
- **~ 1.5 km of line – 8 sources to 16 antenna feeds**

- **Matching network:**
- **Pre-matching system** (reduces VSWR below 4),
- **Decouplers** (reduces mutual coupling between antenna straps & improves matching)
- **Main Matching Unit** (2 stubs: reduce VSWR < 1.5) **+ Hybrid splitter units** (split RF power & provide ELM resilience by diverting reflected power towards DL)

Main Features of ITER IC H&CD System

RF power sources

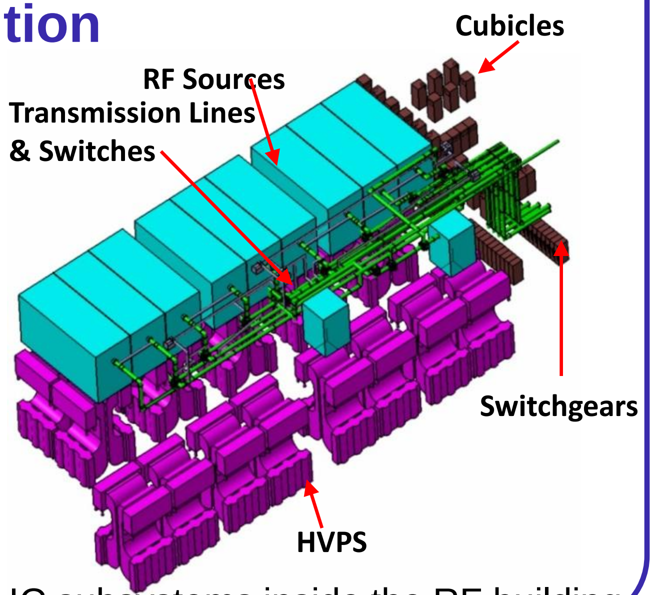
- 9 nos. of RF power sources: 4 sources/antenna + 1 spare
- Each power source will have capability of handling
  - 2.5 MW @ VSWR 2.0 / 35-65 MHz/CW
  - 3.0 MW @ VSWR 1.5 / 40-55 MHz/CW
- Each source is made of 2 // amplifier chains (tube based) with a $\lambda/4$ combiner
- Dynamic control of Va to handle VSWR condition

High Voltage Power Supplies

Regulated 27kV/190A common supply for 2 amp. stages (2 no. of HVPS/source):

– Large number of low-voltage (<1 kV) modules stacked in series,

– Can be switched on/off individually for fine regulation of output voltage

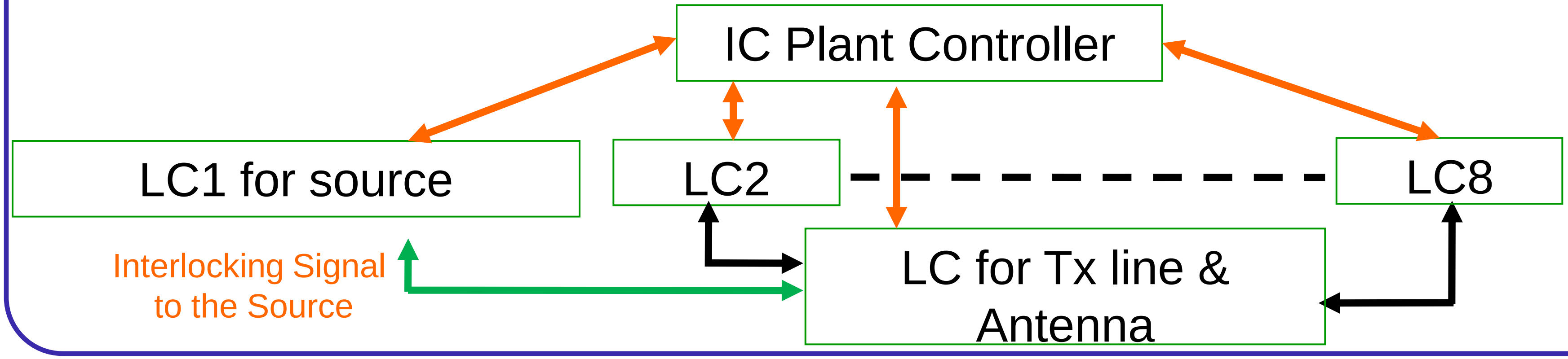


IC subsystems inside the RF building

Main Features of ITER IC H&CD System

Control System:

- **Each IC H&CD subsystem includes a local controller.**
- **Plant Control System (PCS) manages the overall operation, safety and protection:**
  - **Coordination, synchronization**
  - **RF power feedback control**
  - **Conventional control functions, dispatching of all interlocks and safety control functions internal and external to the system**



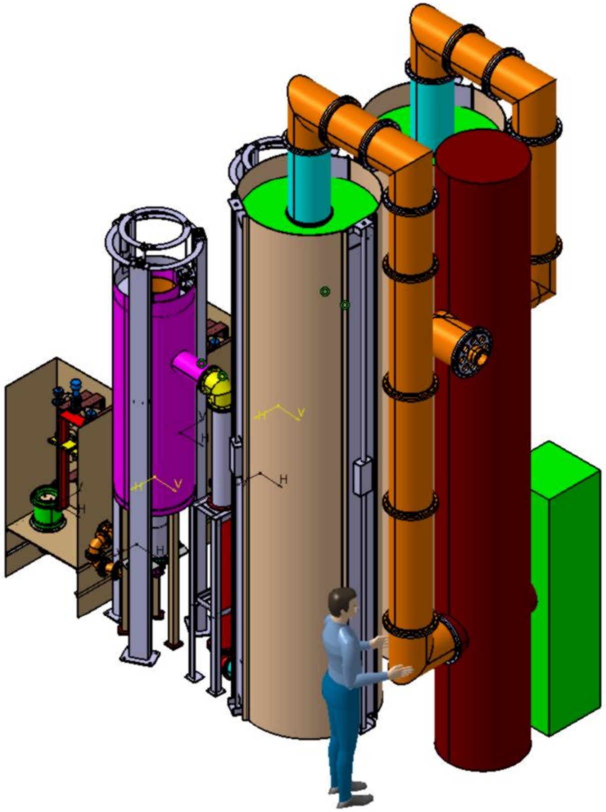
IC Power Source System

Scope & Deliverables

This package is under Functional Specification

Scope includes

- **Design, manufacturing, assembly & testing, packaging & shipment, site commissioning & site acceptance of 1 prototype + 8 RF Sources**



Snapshot of D:\A-Office\RF Chain\Double chain.CATProduct - 02-12-2011 16:20:21

Major sub-system	Qty.
Low power RF section	9 sets
Pre-driver stage amp.	9 sets
Driver stage amplifier	9 sets
Final stage amplifier	9 sets
Auxiliary power supplies	9 sets
Combiner + DL (250kW)	9 sets
RF Electronics	9 sets
Local Control Unit (LCU)	9 sets
Interconnecting Tx-line	As needed
Internal cooling distribution	As needed
Test rig without 3 MW DL	1 set

Functional Specifications for each source

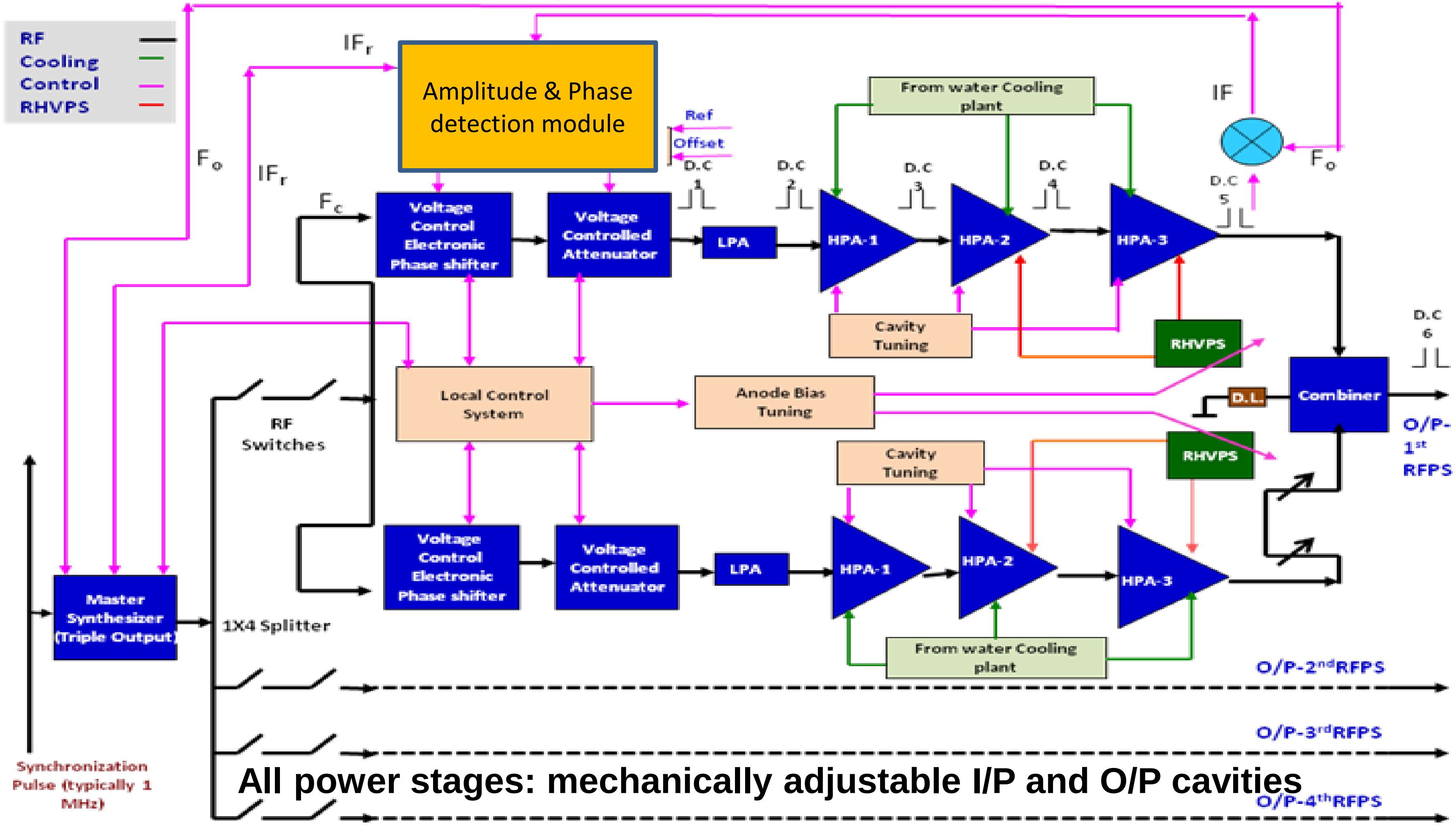
Sr. No.	Parameters	Levels & Units
1	Nominal O/P power / Duty Cycle	2.5 MW / CW / 25%
2	VSWR with any phase ($0 - 360^0$)	2.0
3	Transient VSWR (▵t ~ 1 s) max, 10% duty cycle	2.5 (power can be reduced)
4	Accuracy of the output power	5% of full scale power
5	Frequency range covered	35-65 MHz
6	Frequency deviation over any central frequency (1 dB point)	± 1 MHz
7	Power modulation range	2 kW – 2.5 MW
8	Electrical efficiency	45% - 65% (mismatched – matched)
9	Max. frequency modulation frequency	1 kHz
10	Maximum AM frequency	100Hz
11	Maximum phase modulating frequency	10 kHz
12	Emergency Power shut down	<10 μ S
13	Level of harmonics (dBc)	-20 (on matched load)

Design consideration

- Constant CW output power (2.5 MW) even with VSWR 2 – final stage tube shall withstand such stringent load condition
- Thermal capability of components/subsystems for CW operation (3600s)
- Large power modulation range: 2 kW – 2.5 MW
- 1 dB breakpoint at ± 1 MHz over any central frequency
- Real time control of Amp, Phase & Frequency

Block Diagram of one RF Power Source

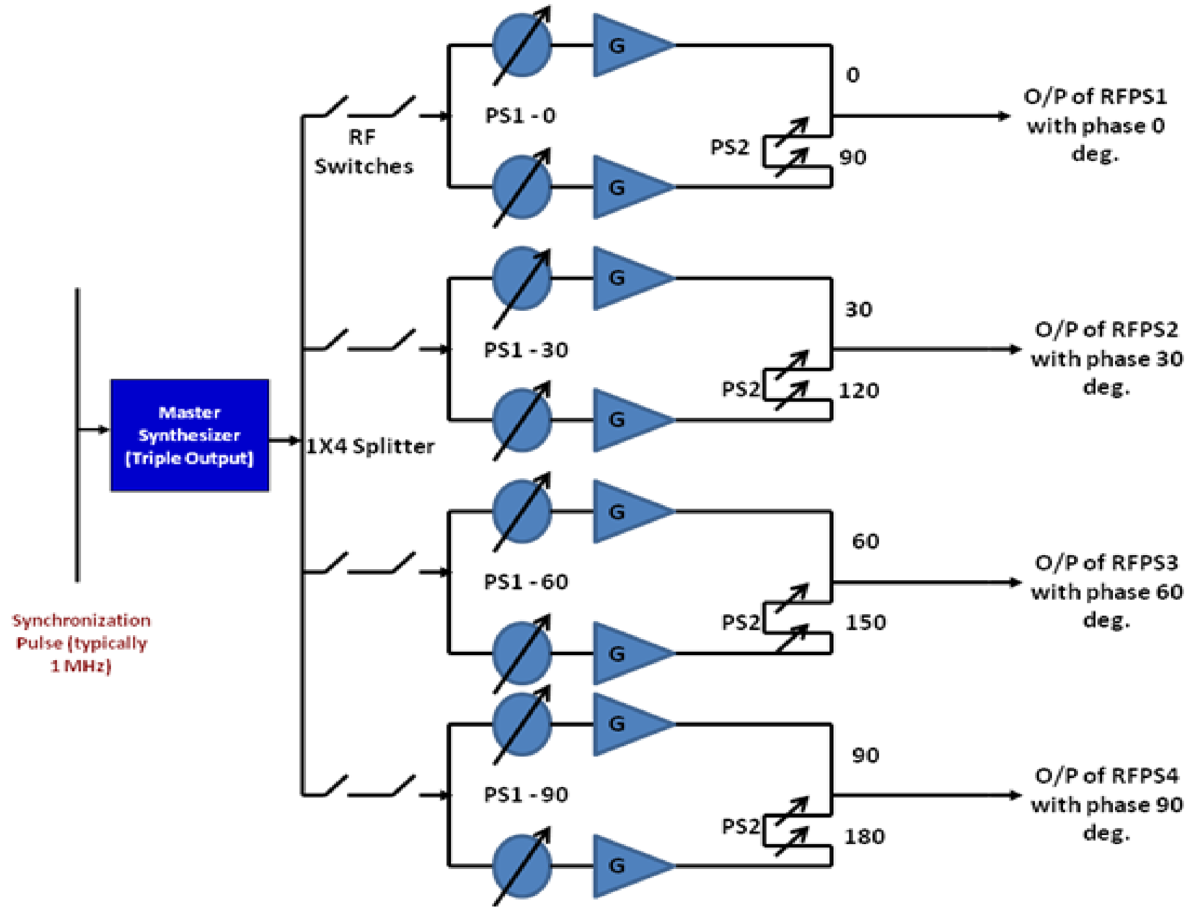
- No single high power tube exists as per ITER requirement
- 1 RF Source: Two independent chain of amplifiers + combiner



All power stages: mechanically adjustable I/P and O/P cavities

Possibility of Phasing

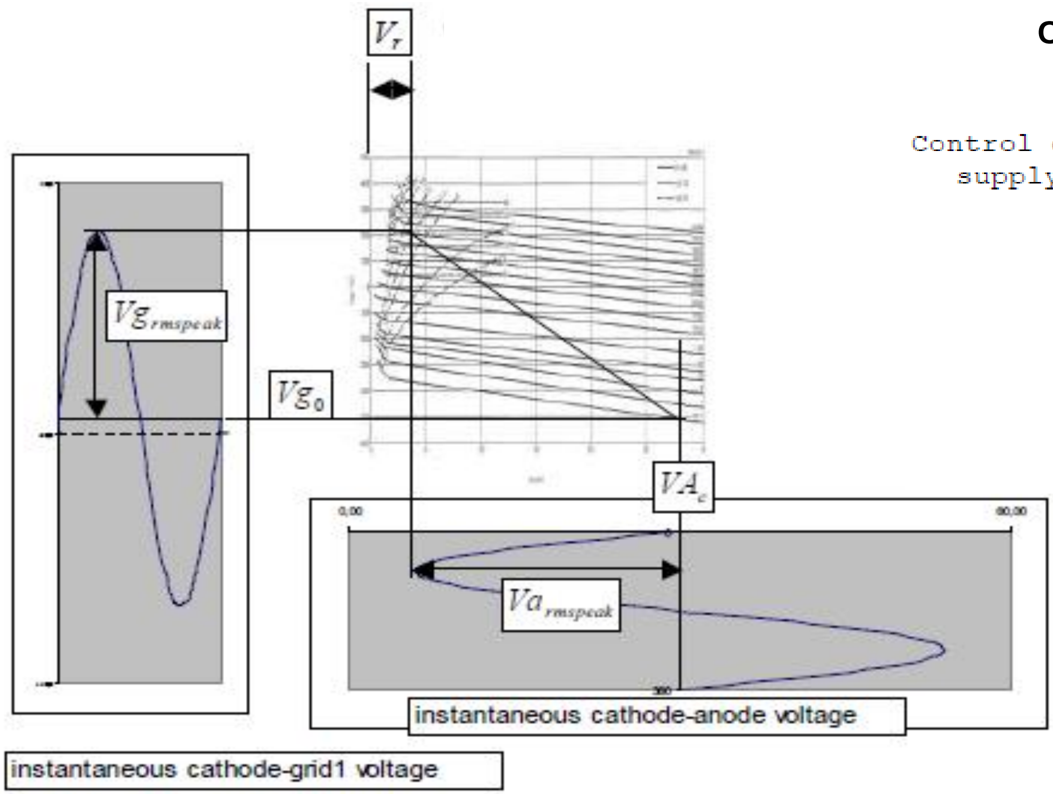
PHASING DETAILS FOR ONE ANTENNA CONNECTED TO FOUR RF SOURCES

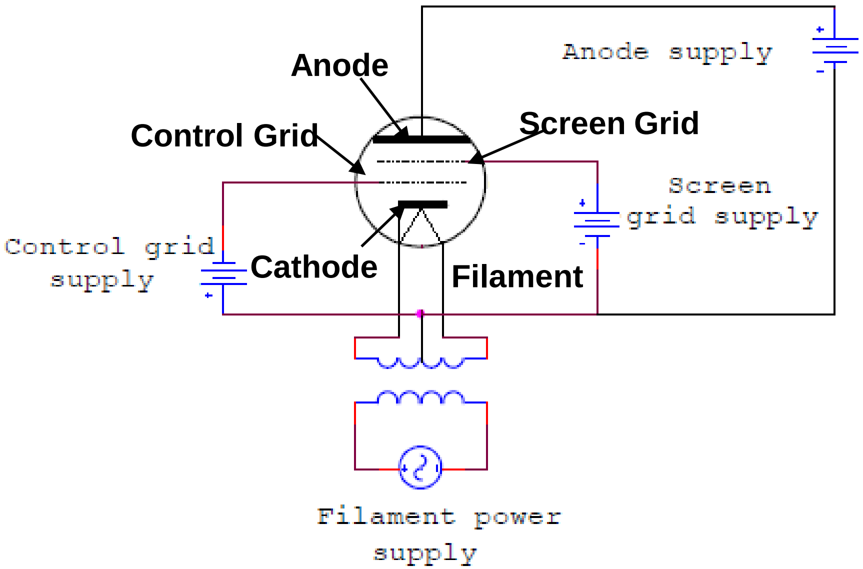


Active device for high power amplifier in MHz frequency range

Tetrodes (4 active electrodes) are often used as active device

$$Vr = V_{dc} - Va_{peak}$$



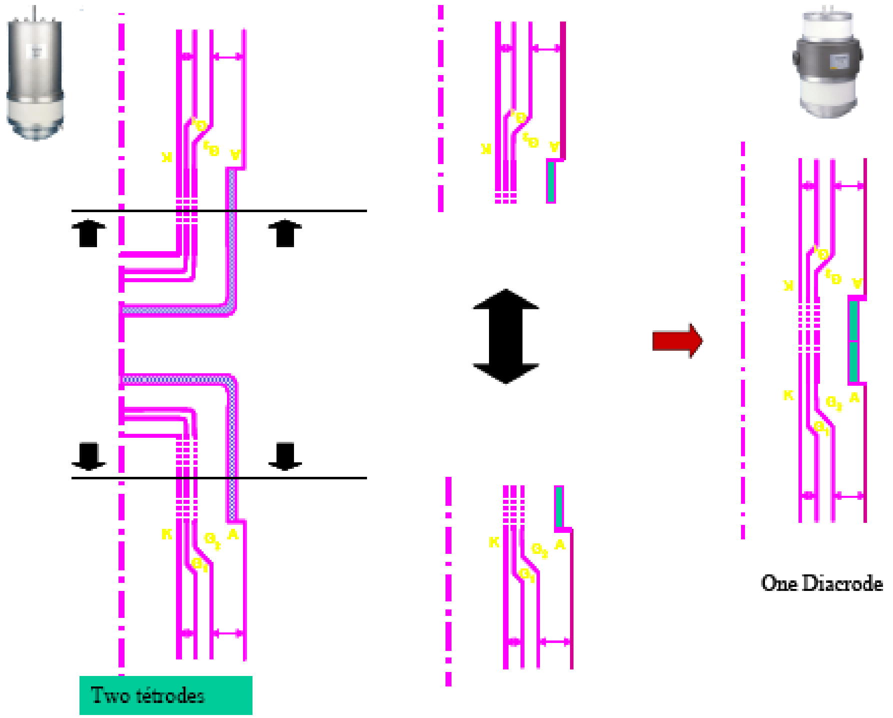


$$\eta = \left(\frac{p}{Vdc * Ia_{av}}\right) = \frac{Va_{peak} * Ia_{peak}}{2 * Vdc * Ia_{av}}$$

Diacrode case

The Diacrode is a double ended Tetrode –

TH628 Diacrode from TED is like 2 halves TH525 put together



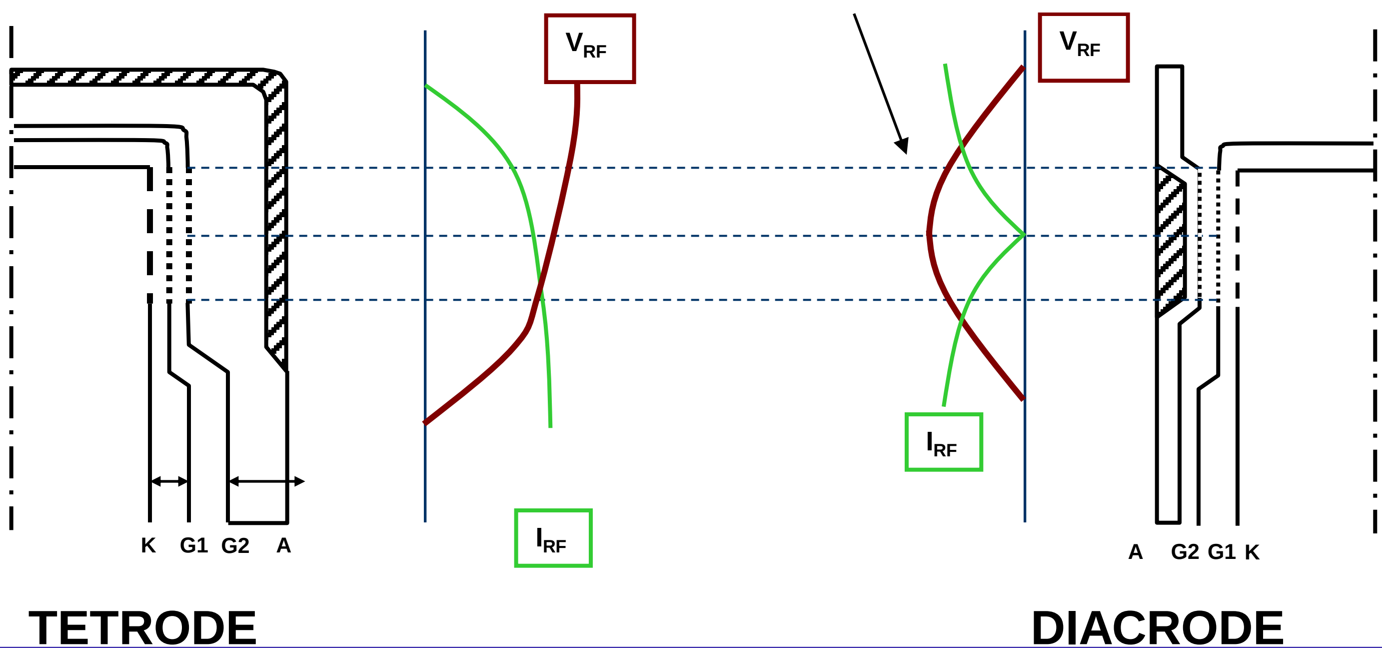
Theoretical curve shows that Diacrode TH628 can deliver in ITER freq. range:

- **2 MW CW on VSWR = 1.5**
- **1.5 MW CW on VSWR = 2**

Tetrode vs. Diacrode

- Diacrode will have 2 output cavities whereas Tetrode will have 1
- Diacrode
  - Allow to adjust the position of the voltage antinode in the resonant circuit formed by the tube and its cavity
  - Possibility of reduction of RF losses, increase in RF peak power, pulse duration & frequency

Maximum RF voltage & Minimum RF current in the middle of the active part.



Status of Tetrode / Diacrode development

ITER Spec	CPI, USA	Thales, EU
2.5 MW at 2 VSWR 2000 s	~1.9 MW /300 s tested on matched load	1 MW /24 hrs. on matched load
50 % - 60 %	> 60 %	> 60%
35 – 65 MHz	30 – 60 MHz	200 MHz

Demonstration of 2.5 MW CW RF power / source @ VSWR 2 (35 – 65 MHz) at any phase angle with other stringent requirements is very challenging

Tetrode Developed by CPI

Anode Connections

Screen connections

Diacrode Developed by Thales

Anode Connections

Screen connections

Technical Challenges involved

- **Combined high power & high VSWR are challenging, even for single chain of amplifiers**
- **CW aspect of the operation further constrains the design as efficient cooling is required for all components**
- **Broad frequency range associated with accurate instantaneous bandwidth (± 1 MHz at 1 dB point) requires specific designs for the tube input and output cavities**
- **Operational problems like, settling time of anode voltage, excess anode dissipation etc., during mismatch situation**
- **Unwanted oscillation & mode generation during operation**
- **Real time control of Amp, Phase & Frequency**

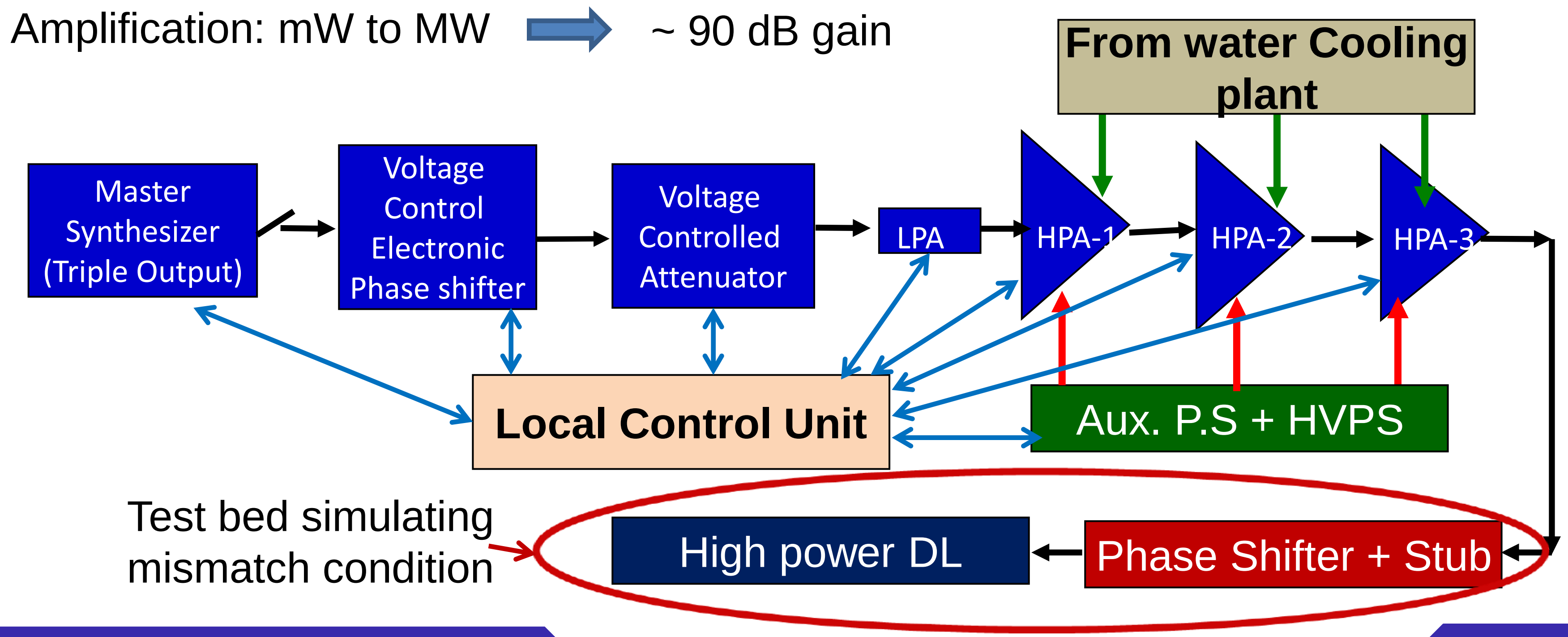
To address major issues

Tube qualification phase using single chain (R&D) experimentation1.5 MW / 3600s / 35 - 65 MHz at VSWR 2.0 with any phase of reflection coefficient launched

![ITER-India]

R&D Activity

- **Final stage is being developed with industrial partner using both kind of technologies (i.e. Tetrode & Diacrode)**
- **Tubes and cavities will be integrated in a full amplifier chain developed by ITER-India**
- **Tests under ITER specifications will validate each design**



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Gain & Power Level

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

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Typical tube specifications

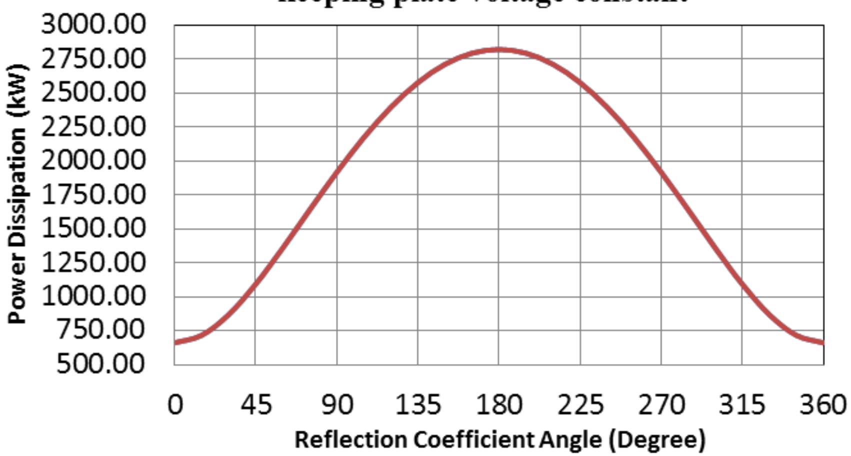
Parameters	Pre-driver Stage (HPA-1)	Driver Stage (HPA-2)	Final Stage (HPA-3)
Type	Tetrode	Tetrode	Tetrode/Diacrode
Max. CW Frequency	110MHz	110MHz	130MHz/200MHz
Filament Voltage	6.3±0.3V	15.5±0.75V	15.5±0.75V/30V
Filament Current	160A	215A	640A/960A
Plate Voltage	10.0kVdc	22.0kVdc	27.0kVdc/30kVdc
Plate Current	6.0Adc	20Adc	190Adc/220A
Plate dissipation	25kW	150kW	**2.5MW/1.8MW**
Screen Voltage	2.0kV	2.5 kV	2.5kV/2.0kV
Screen Dissipation	450W	1750W	20.0kW/14.0kW
Con. grid voltage	-650V	-1500V	-2000V/-1000V
Con. grid dissipation	200W	500W	8.0kW/4.5kW

Influence of VSWR

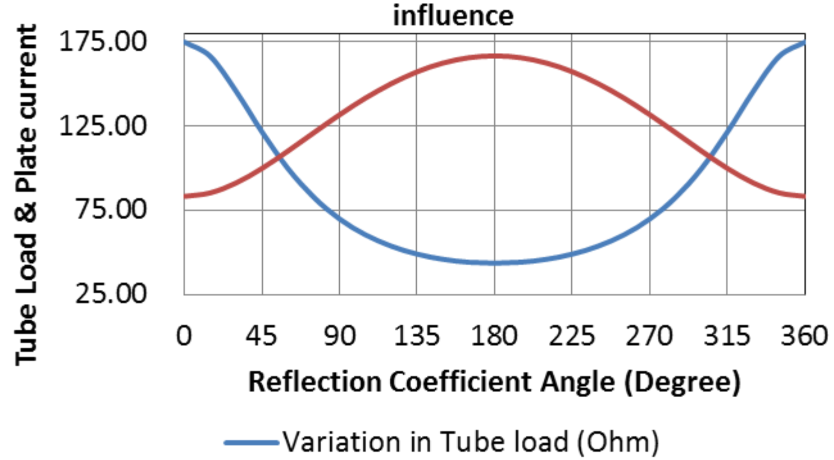
Parameters	RT (Tube Load)	Power in kW	VSWR	Fixed Vr	Theta	Va(dc)
	87.5	1500	2	3000	0.5	25912.88

Reflection angle	RT (Variation)	XT (Variation)	Iavg	Va	Va(dc)	Va(dc)	Pd
(fi)	R	X		(rms Peak)	(Estimated)	(Fixed)	(Fixed)
(Degree)	(Ohm)	(Ohm)	(A)	(Volt)	(Volt)	(Volt)	(kW)
0	175.00	0.00	83.40	22912.88	25912.88	25912.88	660.93
45	121.58	64.48	100.05	21617.97	24617.97	25912.88	1092.52
90	70.00	52.50	131.86	18114.22	21114.22	25912.88	1916.73
135	49.15	26.06	157.36	13744.58	16744.58	25912.88	2577.62
180	43.75	0.00	166.79	11456.44	14456.44	25912.88	2821.86
225	49.15	-26.06	157.36	13744.58	16744.58	25912.88	2577.62
270	70.00	-52.50	131.86	18114.22	21114.22	25912.88	1916.73
315	121.58	-64.48	100.05	21617.97	24617.97	25912.88	1092.52
360	175.00	0.00	83.40	22912.88	25912.88	25912.88	660.93

Plate dissipation variation with VSWR influence keeping plate voltage constant



Tube load & Plate current variation with VSWR influence



Management of excess plate dissipation

Parameters	RT (Tube Load)	Power in kW	VSWR	Fixed Vr	Theta	Vdc
	87.5	1500	2	3000	0.5	25912.88

reflection angle (fi) (Degree)	RT (Variation) R (Ohm)	XT (Variation) X (Ohm)	Iavg (A) (A)	Va (rms Peak) (Volt)	Va(dc) (Estimated) (Volt)	Va(dc) (Variable) (Volt)	Pd (Variable) (kW)
0	175.00	0.00	83.40	22912.88	25912.88	25912.88	661.01
45	121.58	64.48	100.05	21617.97	24617.97	24617.97	963.05
90	70.00	52.50	131.86	18114.22	21114.22	21114.22	1284.10
135	49.15	26.06	157.36	13744.58	16744.58	15500.00	939.14
180	43.75	0.00	166.79	11456.44	14456.44	15500.00	1085.25
225	49.15	-26.06	157.36	13744.58	16744.58	15500.00	939.14
270	70.00	-52.50	131.86	18114.22	21114.22	21114.22	1284.10
315	121.58	-64.48	100.05	21617.97	24617.97	24617.97	963.05
360	175.00	0.00	83.40	22912.88	25912.88	25912.88	661.01

Dynamic control of Va

Plate dissipation with VSWR influence keeping plate voltage variable

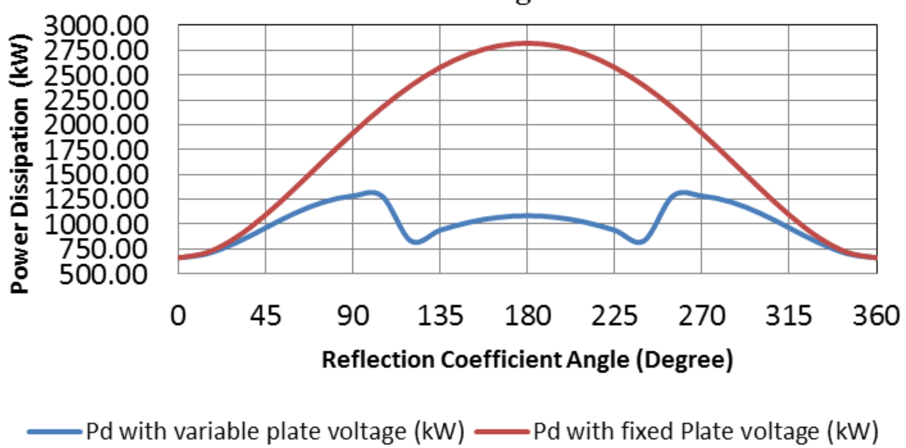
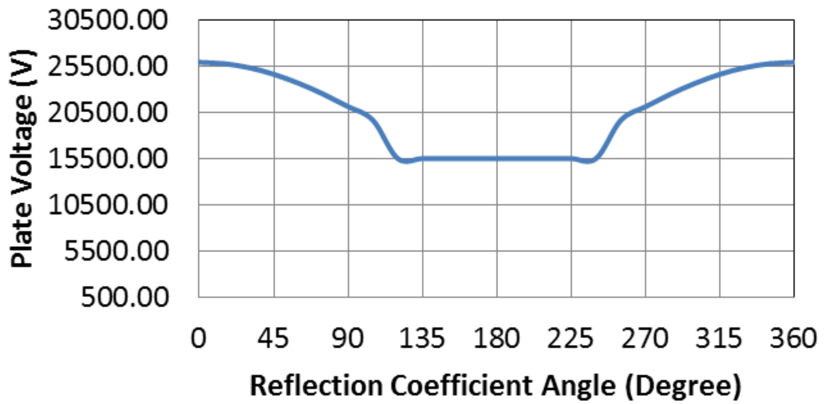


Plate voltage Variation during VSWR to control excess plate dissipation



Cases with different tube load

Parameters	RT (Tube Load)	Power in kW	VSWR	Fixed Vr	Theta	Vdc
	90	1500	2	3000	0.5	26237.90

reflection angle	RT (Variation)	XT (Variation)	Iavg	Va	Va(dc)	Va(dc)	Pd
(fi)	R	X	(A)	(rms Peak)	(Estimated)	(Fixed)	(fixed)
(Degree)	(Ohm)	(Ohm)	(A)	(Volt)	(Volt)	(Volt)	(kW)
0	180.00	0.00	82.23	23237.90	26237.90	26237.90	657.51
45	125.06	66.32	98.65	21924.62	24924.62	26237.90	1088.41
90	72.00	54.00	130.01	18371.17	21371.17	26237.90	1911.32
135	50.55	26.81	155.16	13939.54	16939.54	26237.90	2571.15
180	45.00	0.00	164.46	11618.95	14618.95	26237.90	2815.01
225	50.55	-26.81	155.16	13939.54	16939.54	26237.90	2571.15
270	72.00	-54.00	130.01	18371.17	21371.17	26237.90	1911.32
315	125.06	-66.32	98.65	21924.62	24924.62	26237.90	1088.41
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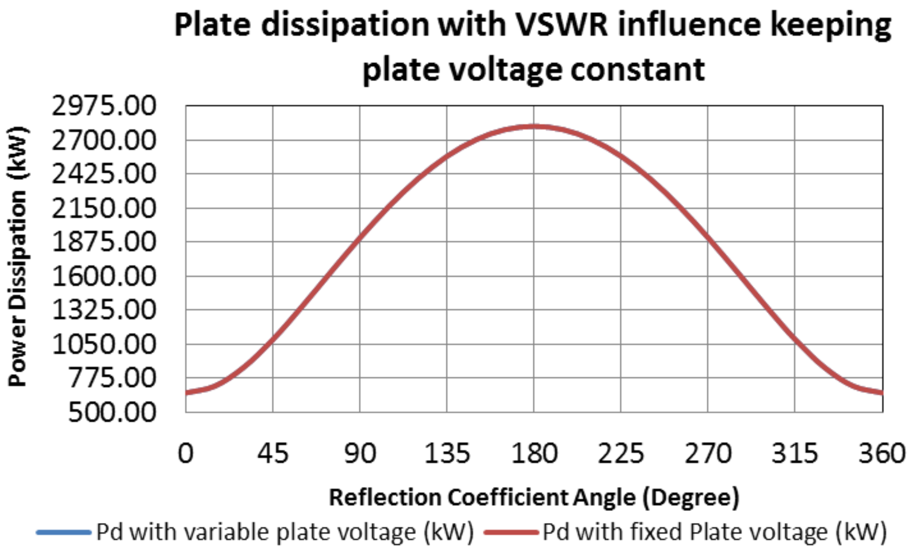
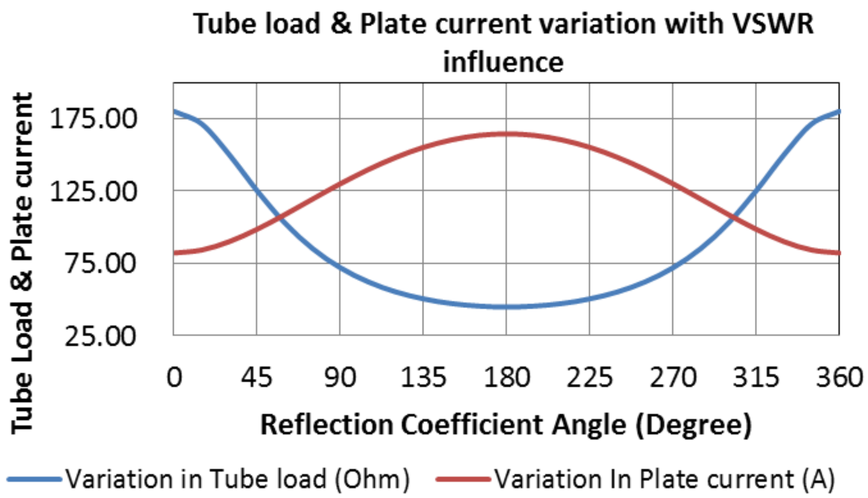




Management of dissipation

Prameters	RT (Tube Load)	Power in kW	VSWR	Fixed Vr	Theta	Vdc
	90	1500	2	3000	0.5	26237.90

reflection angle	RT (Variation)	XT (Variation)	Iavg	Va	Va(dc)	Va(dc)	Pd
(fi)	R	X	(A)	(rms Peak)	(Estimated)	(Variable)	(Variable)
(Degree)	(Ohm)	(Ohm)	(A)	(Volt)	(Volt)	(Volt)	(kW)
0	180.00	0.00	82.23	23237.90	26237.90	26237.90	657.51
45	125.06	66.32	98.65	21924.62	24924.62	24924.62	958.86
90	72.00	54.00	130.01	18371.17	21371.17	21371.17	1278.57
135	50.55	26.81	155.16	13939.54	16939.54	16939.54	1128.39
180	45.00	0.00	164.46	11618.95	14618.95	15500.00	1049.09
225	50.55	-26.81	155.16	13939.54	16939.54	16939.54	1128.39
270	72.00	-54.00	130.01	18371.17	21371.17	21371.17	1278.57
315	125.06	-66.32	98.65	21924.62	24924.62	24924.62	958.86
360	180.00	0.00	82.23	23237.90	26237.90	26237.90	657.51

Dynamic control of Va

Plate dissipation with VSWR influence keeping plate voltage variable

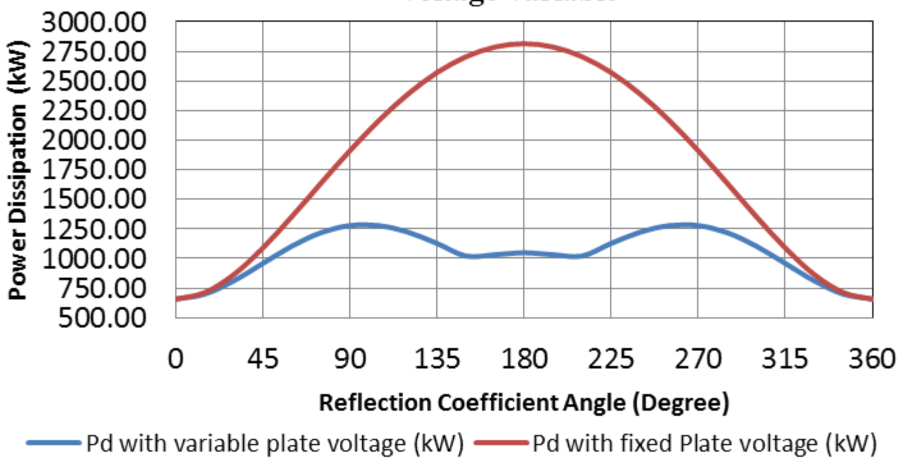
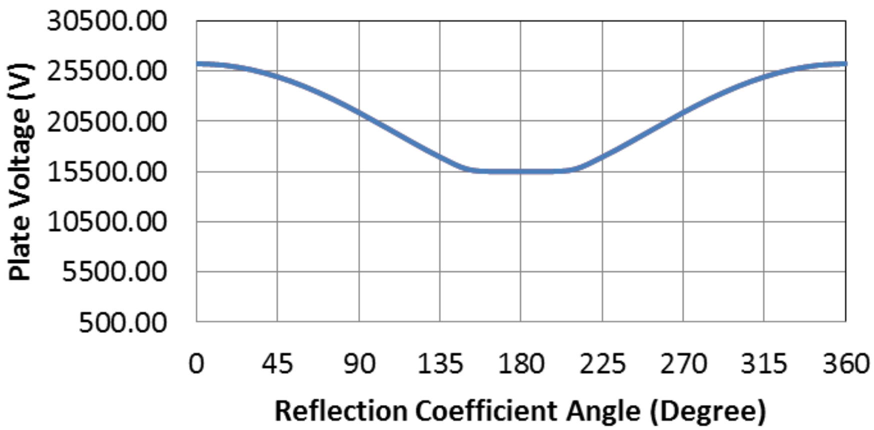
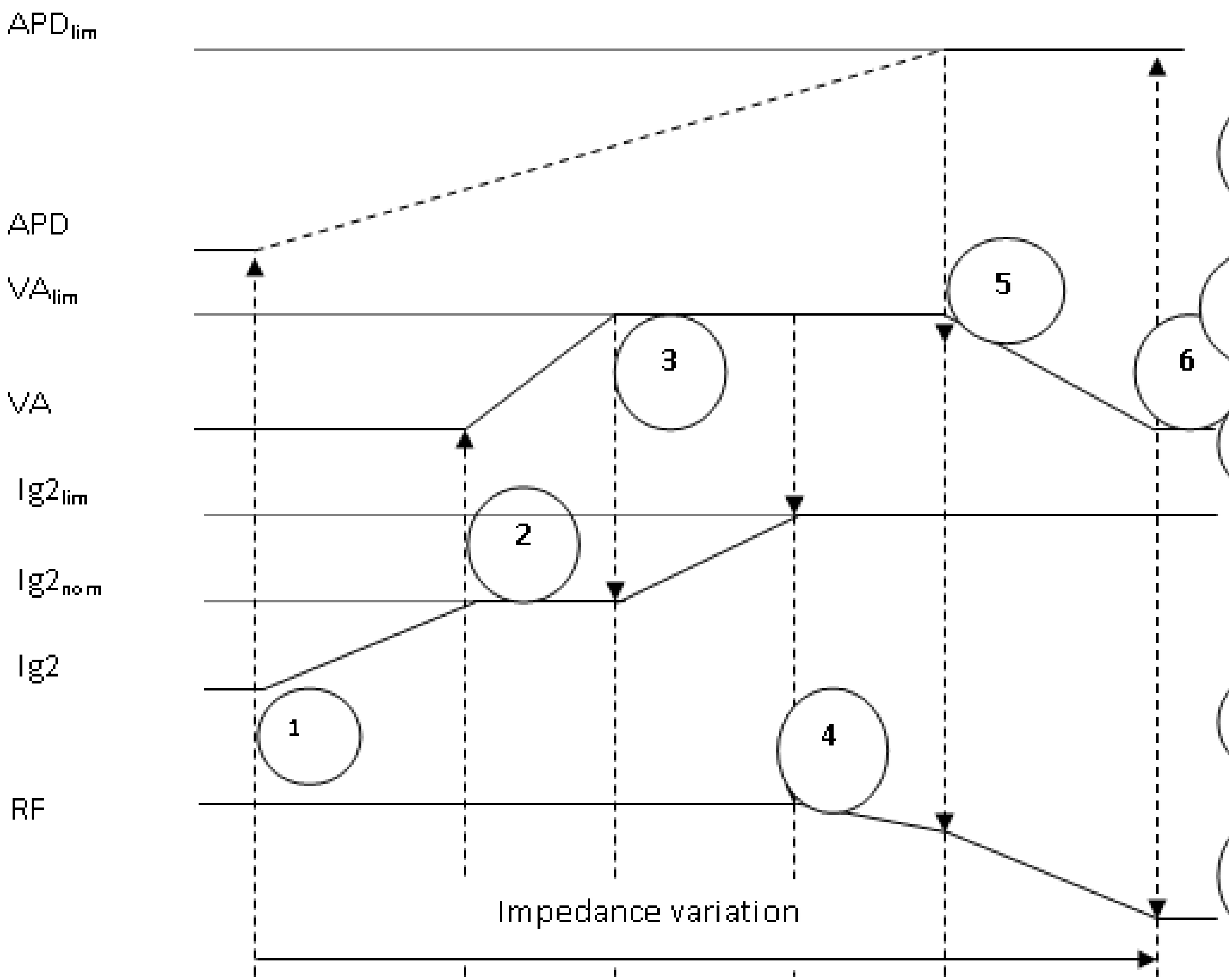


Plate voltage Variation during VSWR to control excess plate dissipation

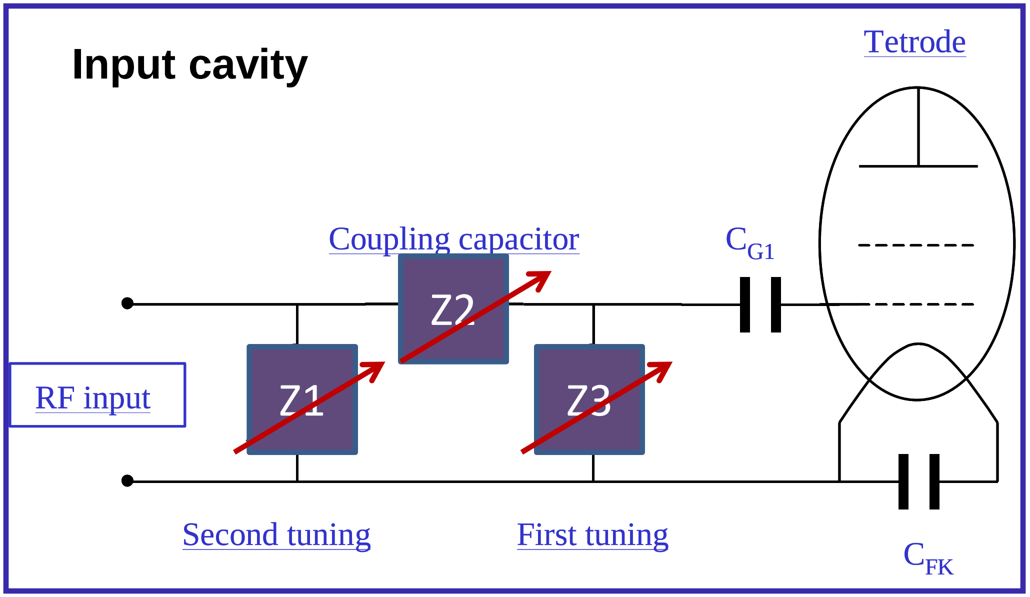


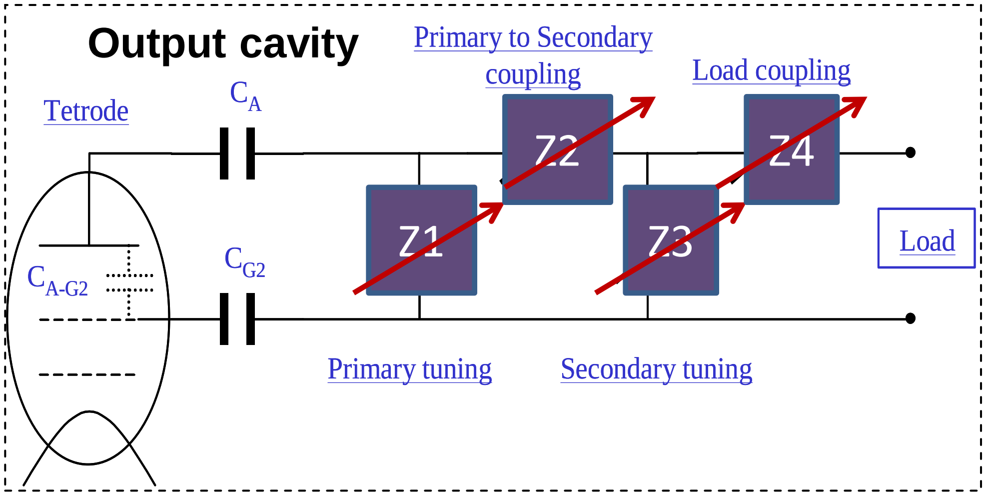
Va Loop



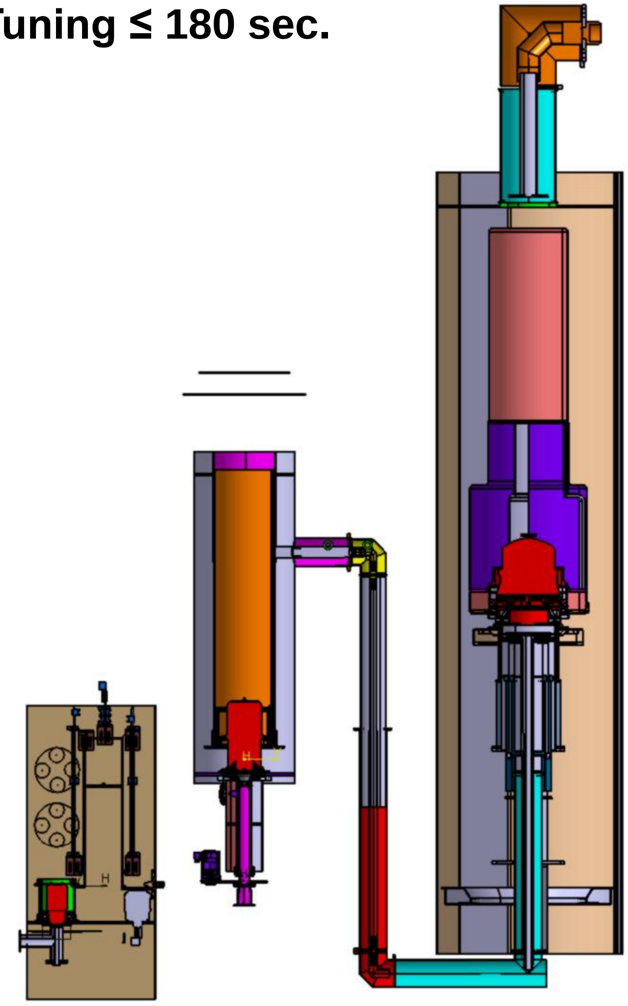
1. Ig2 & APD rise due to Impedance Variation
2. $Ig2 = Ig2_{nom}$ causes VA to rise
3. $VA = VA_{lim}$ causes Ig2 to rise
4. $Ig2 = Ig2_{lim}$ causes RF to decrease
5. $APD = APD_{lim}$ causes VA to decrease
6. System stabilized on lower level due to stable impedance

Cavity design for Input & Output





No. of motors for each chain = 18
Tuning ≤ 180 sec.



Snapshot of D:\A-Office\RF Chain\Single Chain.CATProduct - 02-12-2011 16:31:34

ITER-India

Power Supply requirements

HPA-1

Anode PS
- Voltage : 6.5 kV DC
- Current : 5 Amp
- Regulation : 1 % Line & Load
- Ripple : 1 % P-P @ 5 kV
- Store energy < 10 Joule

Screen Grid PS
- Voltage : 1.5 kV DC
- Current : 1 Amp
- Bleeder : 0.5 Amp
- Regulation : 1 % Line & Load
- Ripple : 1 % P-P
- Store energy < 10 Joule

Control Grid PS
- Voltage : - 800 V DC
- Current : 500 mAmp
- Regulation : 1 % Line & Load
- Ripple : 1 % P-P
- Store energy < 10 Joule

Filament PS
- Voltage : 8.8 DC/AC
- Current : 200 Amp
- Ramp up / Ramp down : > 5 Min

HPA-2

Anode PS
- Voltage : 15 kV DC
- Current : 20 Amp
- Regulation : 1 % Line & Load
- Ripple : 1 % P-P @18 kV
- Store energy < 10 Joule

Screen Grid PS
- Voltage : 2 kV DC
- Current : 2 Amp
- Bleeder : 0.5 Amp
- Regulation : 1 % Line & Load
- Ripple : 1 % P-P
- Store energy < 10 Joule

Control Grid PS
- Voltage : - 1000 V DC
- Current : 1.5 Amp
- Bleeder : 3.75A @ -500V
- Regulation : 1 % Line & Load
- Ripple : 1 % P-P
- Store energy < 10 Joule

Filament PS
- Voltage : 10 V DC
- Current : 400 Amp
- Ramp up / Ramp down : 8 Min

HPA-3

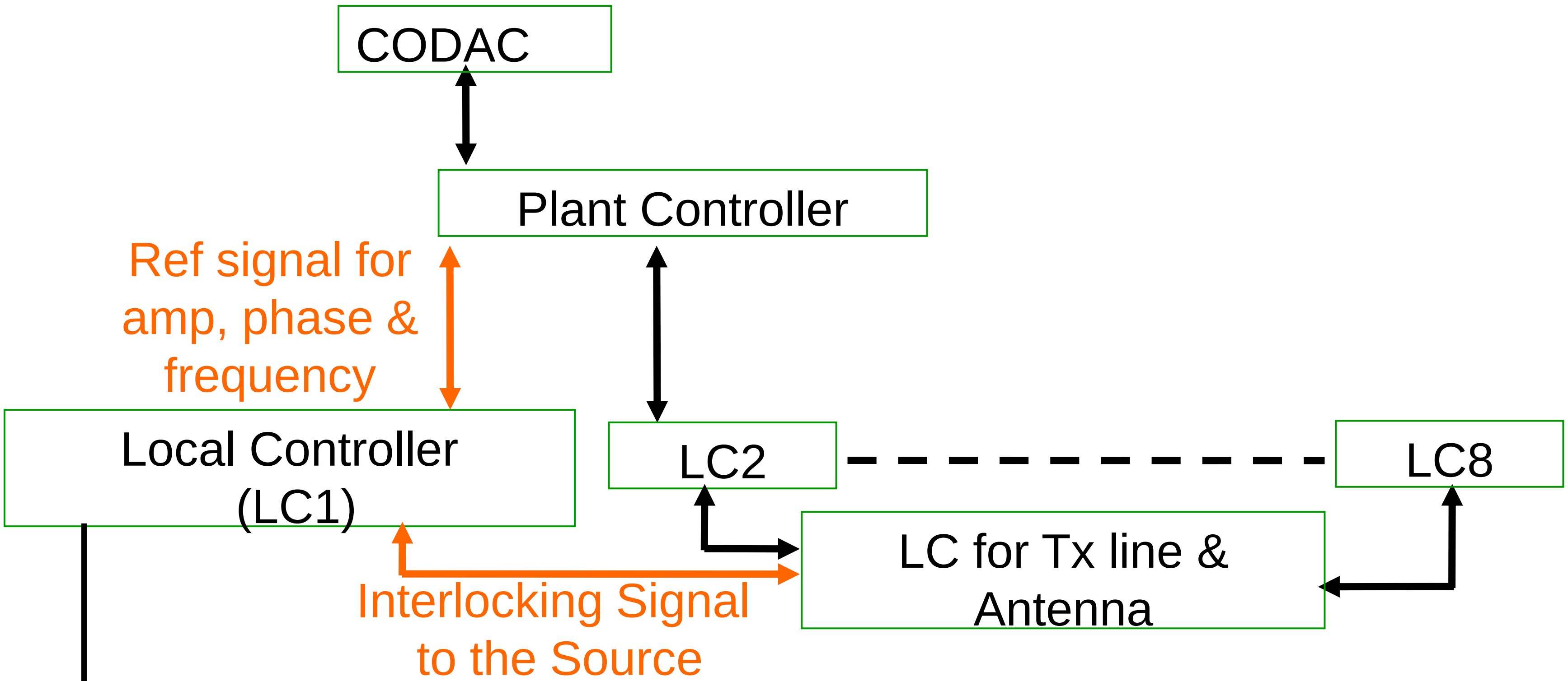
Anode PS
- Voltage : 15.5 - 27 kV DC
- Current : 190 Amp
- Regulation : 1 % Line & Load
- Ripple : 1 % P-P @ 27 kV
- Store energy < 10 Joule

Screen Grid PS
- Voltage : 2 kV DC
- Current : 8 Amp
- Bleeder : 1 Amp
- Regulation : 1 % Line & Load
- Ripple : 1 % P-P
- Store energy < 10 Joule

Control Grid PS
- Voltage : - 1000 V DC
- Current : 6 Amp
- Bleeder : 10 A @ - 500 V
- Regulation : 1 % Line & Load
- Ripple : 1 % P-P
- Store energy < 10 Joule

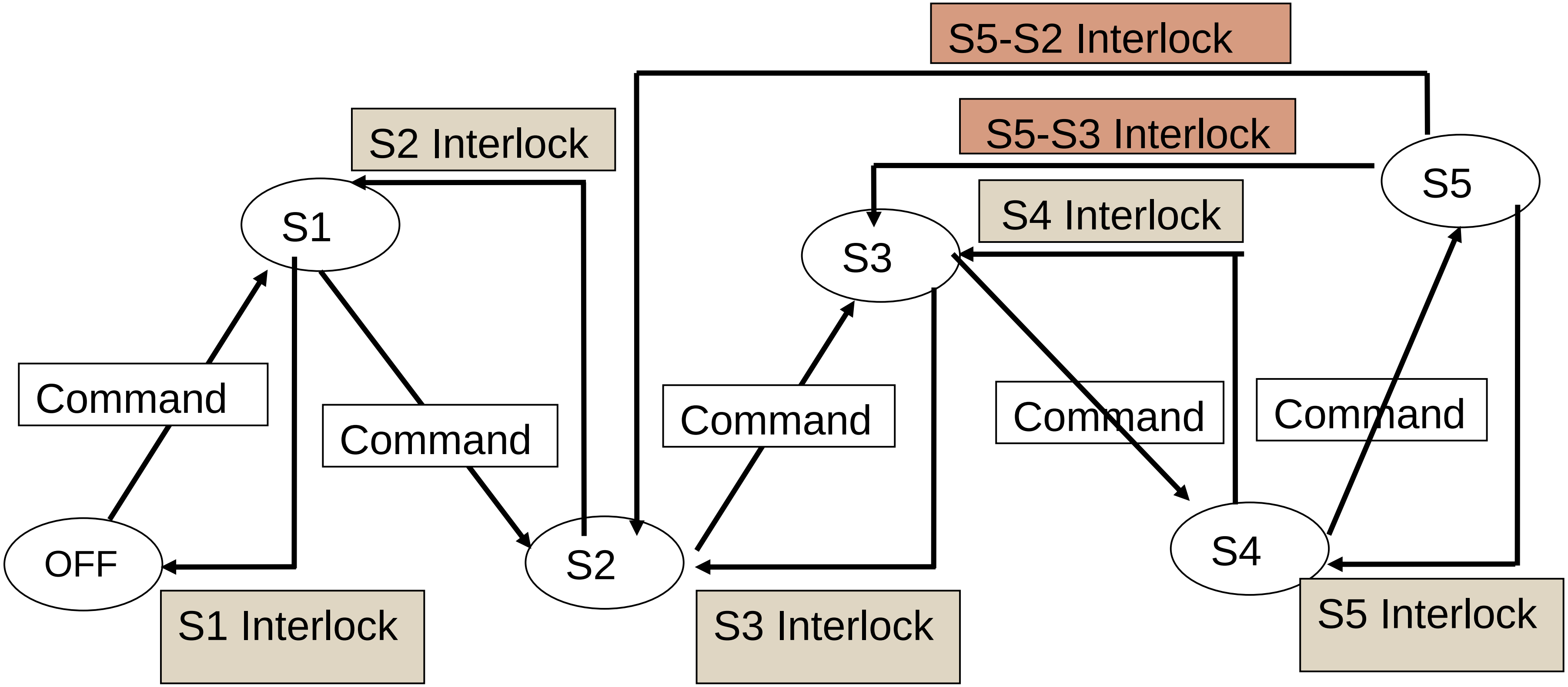
Filament PS
- Voltage : 20 VDC
- Current : 1200 Amp
- Ramp up / Ramp down : 8 Min

3-Tier Data Acquisition & control system for ITER



- PLC based Sequential operational system with safety Interlock
- Real time control loop, Fast acquisition & On line monitoring
- Fast interlock with pre & post triggering acquisition(<1µsec)
- Display module for online & offline analysis
- Cavity Tuning for different frequency operation

State Diagram for Sequence control



S0 →Off state

S1→Stand By (Auxiliary On)

S2→Heater & VG1 ON

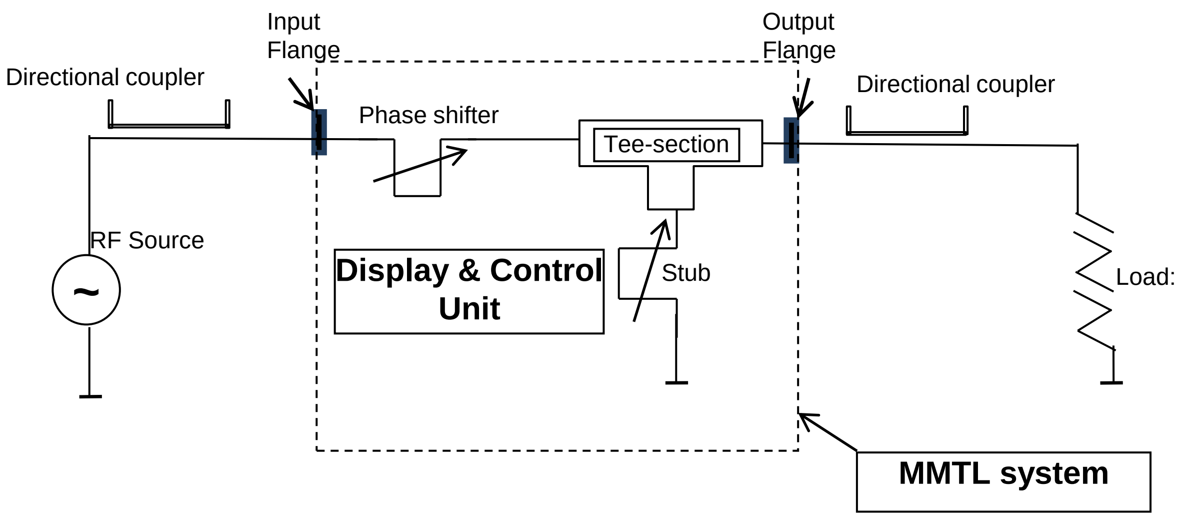
S3→Anode Voltage On

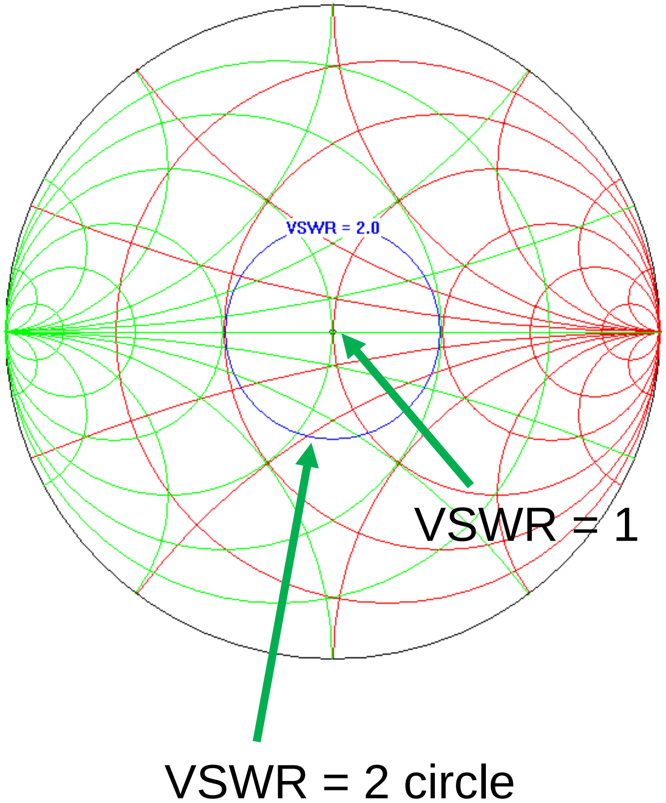
S4→VG2 ON

S5→RF ON

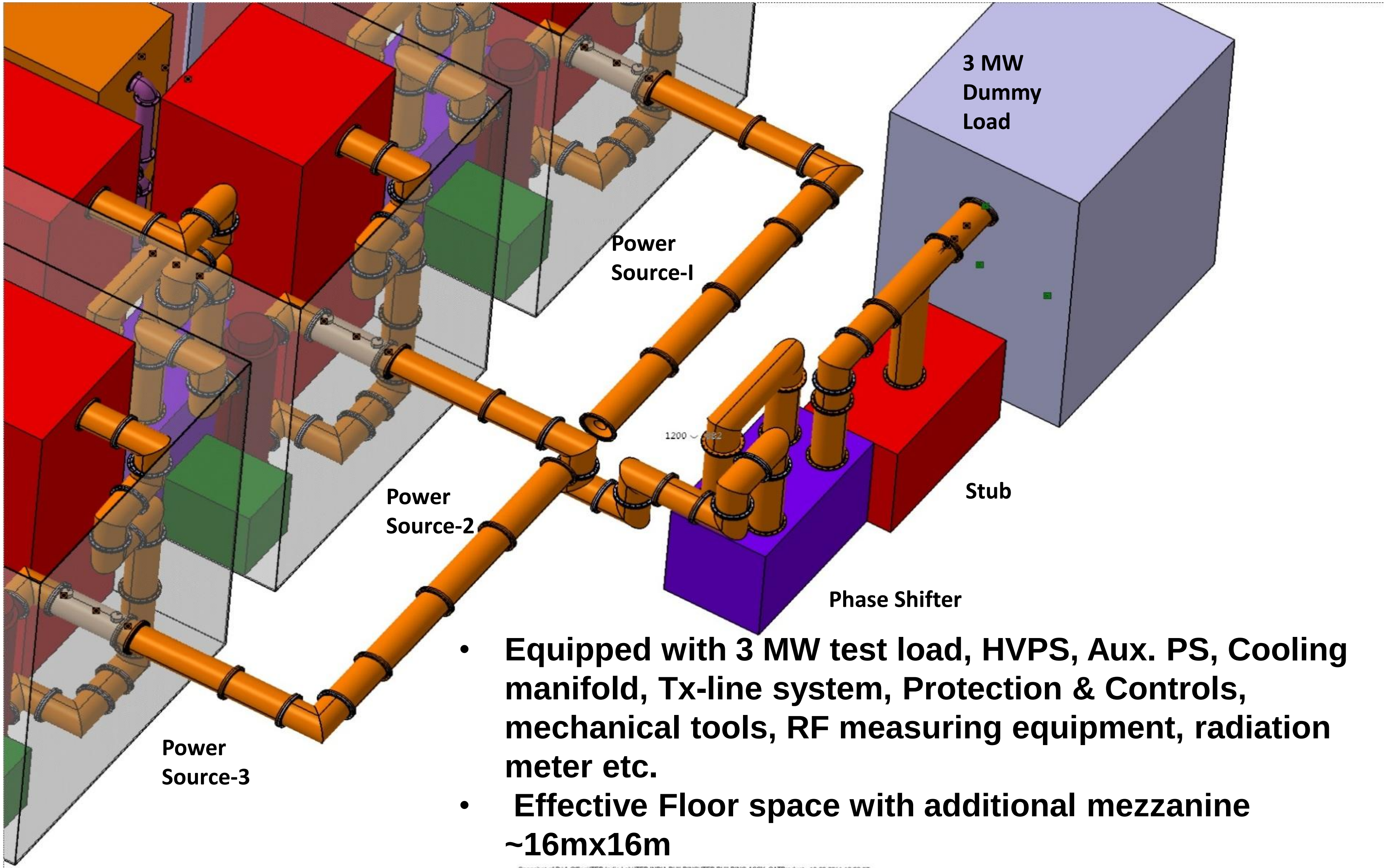
3MW/3600s/35-65 MHz test setup

Load impedance *ZT* = *R* + *jX* covers the entire circle



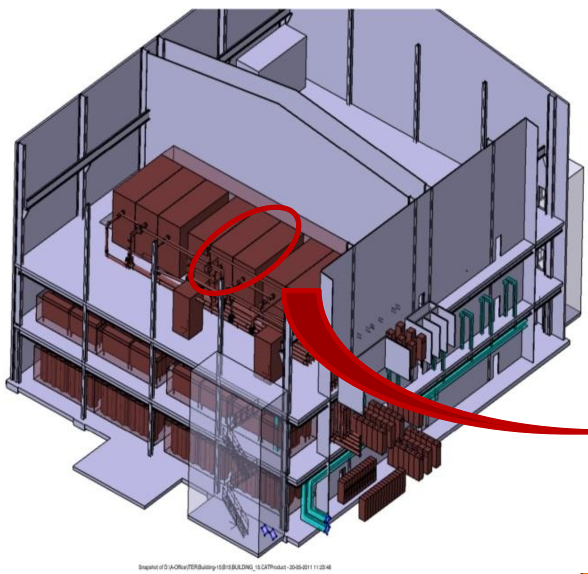


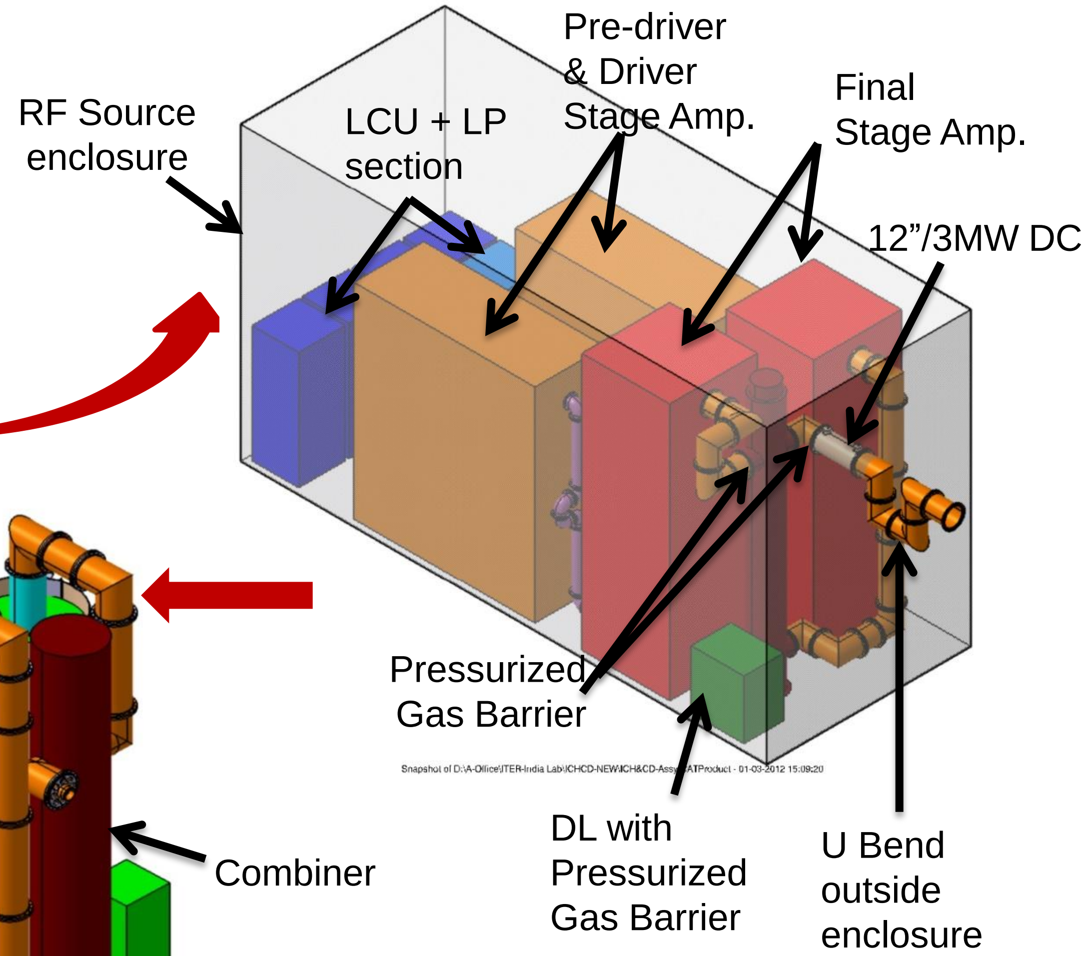
High Power Test Facility

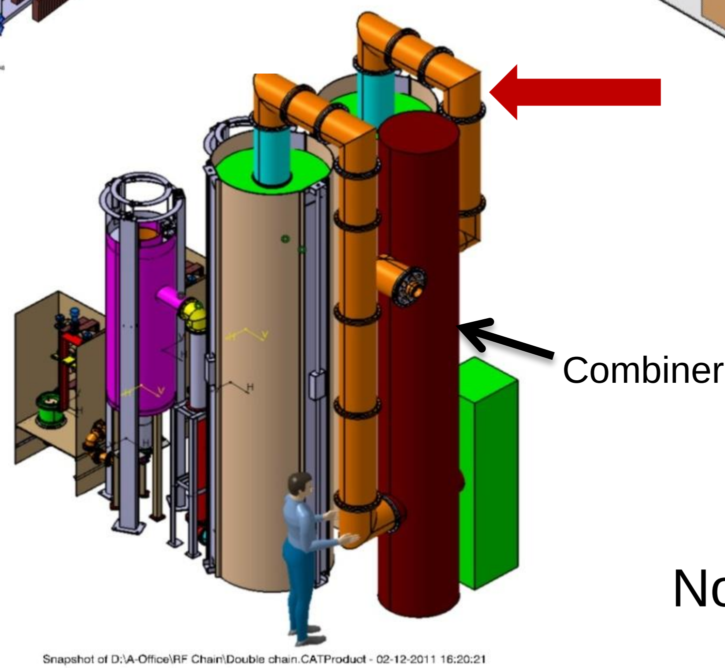


- Equipped with 3 MW test load, HVPS, Aux. PS, Cooling manifold, Tx-line system, Protection & Controls, mechanical tools, RF measuring equipment, radiation meter etc.
- Effective Floor space with additional mezzanine ~16mx16m
- Clear Height > 7.5 m

IC Power Source at ITER-RF building







Note: End of U bend is IN-US Interface

Summary

- **RF Source for ITER will cover all scenarios required from operational point of view**
- **Very special design is involved to satisfy major requirements**
- **To identify critical components involved, specially in high power stage, R&D activity has been initiated considering different type of vacuum tubes (Tetrode & Diacrode)**
- **Outcome of R&D phase will lead to establish the technology, capable of delivering the ITER ICRF source specifications with reliability**