ECRH systems in tokamak SST-1 and Aditya

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Plan of Talk

- Introduction in short to ECRH in tokamak Plasma
  - (Launching of ECRH in SST-1 and Aditya)
- 82.6GHz ECRH System on SST-1
  - (Gyrotron, transmission line and launcher)
- 42GHz ECRH system on SST-1
  - (Gyrotron, transmission line and launcher)
- 42GHz ECRH System on Aditya
- Future plan
- Summary

Applications of ECRH

- ECRH for reliable start-up in tokamak at lower loop voltage and even at higher error magnetic field
- ECRH for plasma heating
- ECCD and NTM suppression / plasma control
- Gyrotron's further application on diagnostics – CTS
- Other experiment related to plasma wall interaction in linear devices
- **So ECRH a very promising heating scheme in fusion plasma**

Terminology (ECR waves in plasma):

In a homogeneous plasma the two possible modes are given by well known Appleton Hartree dispersion relation, for a wave propagating at an angle θ to the toroidal magnetic field B is :

$$N^2 = \frac{c^2 k^2}{\omega^2} = 1 - \frac{2\alpha\omega^2 (1-\alpha)}{2\omega(1-\alpha) - \omega^2_{ce} \mathrm{Sin}\theta \pm \omega_{ce}\Gamma}$$

The +ve sign is for O-mode where as -ve sign is for X-mode.

$$\Gamma = [\omega_{ce} \sin^4\theta + 4\omega^2 (1-\alpha)^2 \cos^2\theta]^{1/2} \quad \& \quad \alpha = \omega^2_{pe} / \omega^2$$

Where k is the propagation vector , ω is operating frequency , ω_{ce} is cyclotron frequency , ω_{pe} is plasma frequency (in rad./sec) , N is the refractive index and θ is the angle between propagation vector and magnetic field.

The condition for cyclotron resonance can be expressed as :

$$\omega = \omega_{ce} + k_{||} v_{||}$$

Type of modes in ECR Plasma

O-Mode: If $\theta = \pi / 2$, O-mode is independent of magnetic field & the dispersion relation is given as :

$$N^2 = 1 - \frac{\omega_{pe}^2}{\omega^2}$$

For X-mode, dispersion relation is:

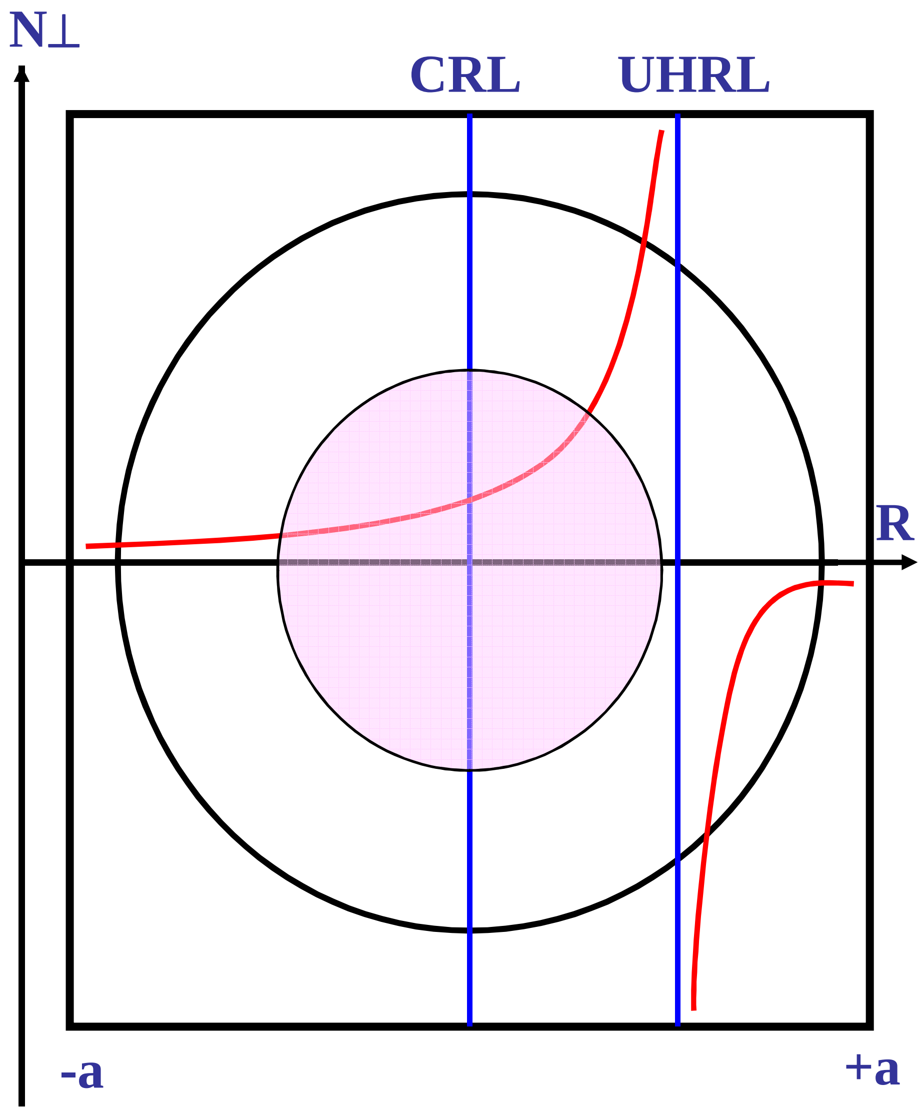
$$N^2 = \frac{[\omega(\omega - \omega_{ce}) - \omega_{pe}^2][\omega(\omega + \omega_{ce}) - \omega_{pe}^2]}{\omega^2(\omega^2 - \omega_{pe}^2 - \omega_{ce}^2)}$$

If, $N = 0$. Cut Off, $N = \infty$ Resonance

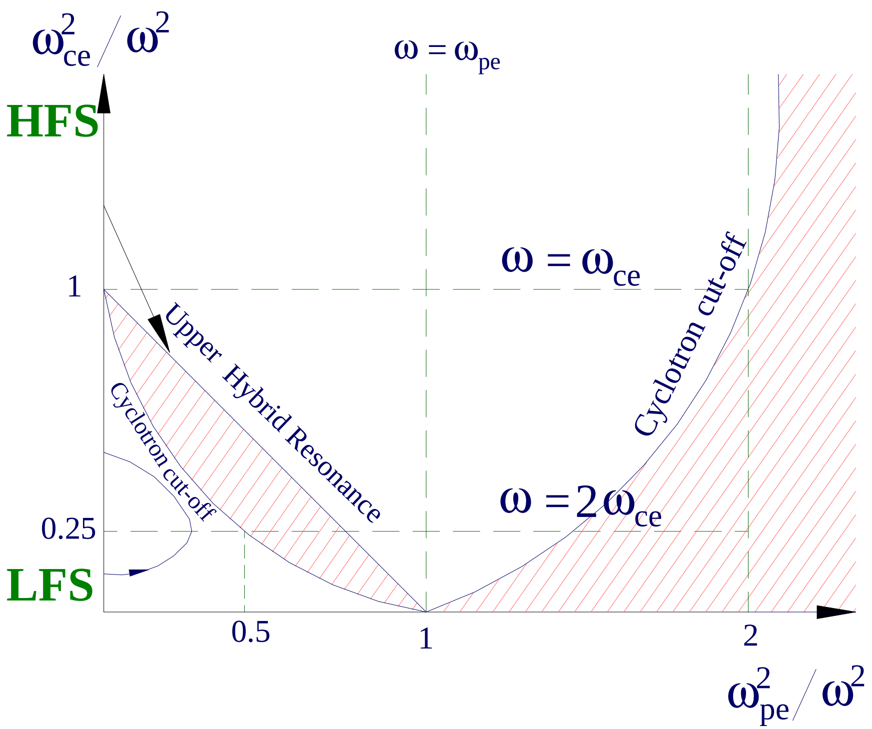
For O- mode, $N = 0$, at $\omega = \omega_{pe}$ (Density cut off)

At, $\omega^2 = \omega_{pe}^2 + \omega_{ce}^2 = \omega_{uh}^2$

$N = \infty$ Resonance (Upper hybrid Resonance)

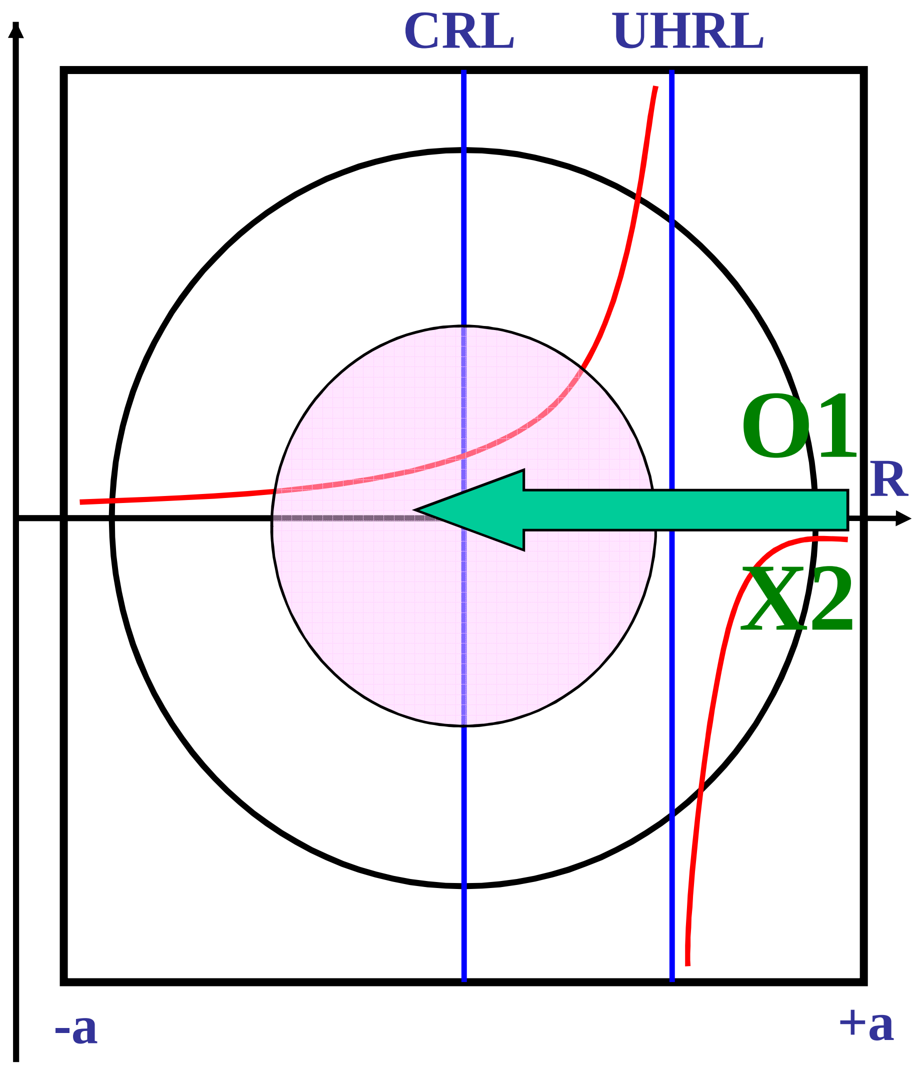


Theory (CMA Diagram and density cut offs):

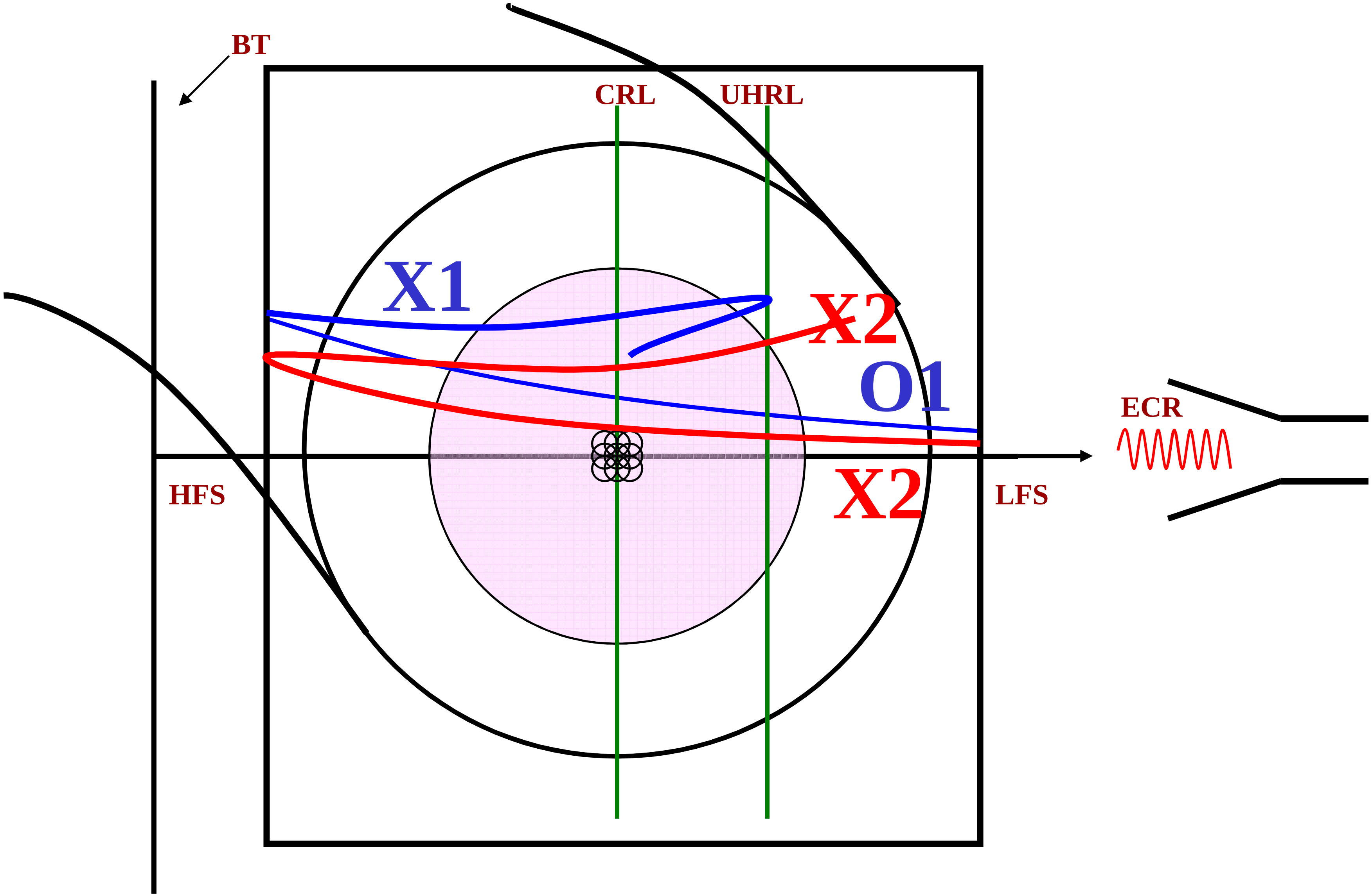


w = wce

w = 2wce



Low field side launch of O1 and X2



ECRH systems in Tokamak SST-1 and Aditya

HFS is not feasible in SST-1 and Aditya

low field side (LFS) launch of O_1 and X_2

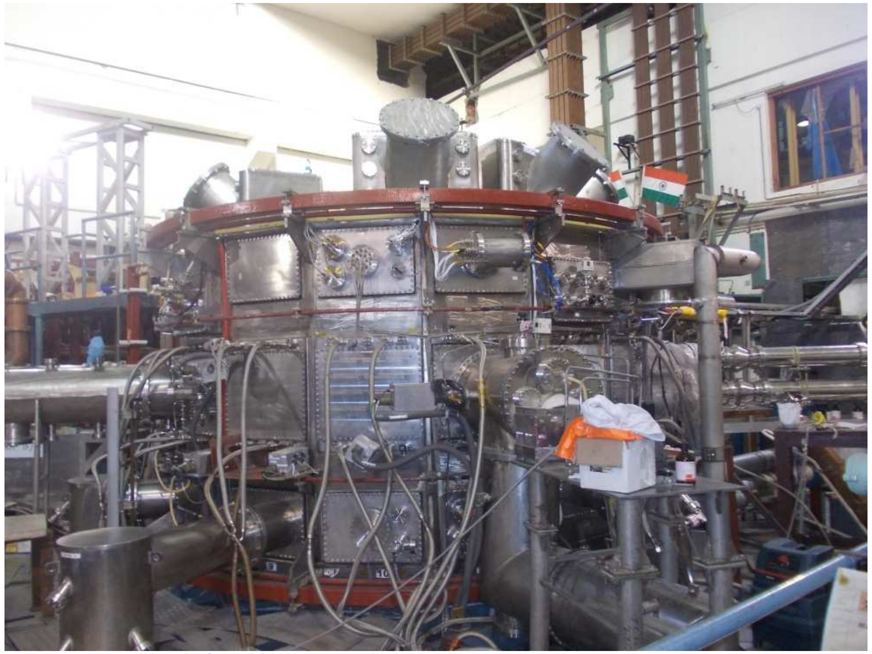
SST-1 ECRH systems:

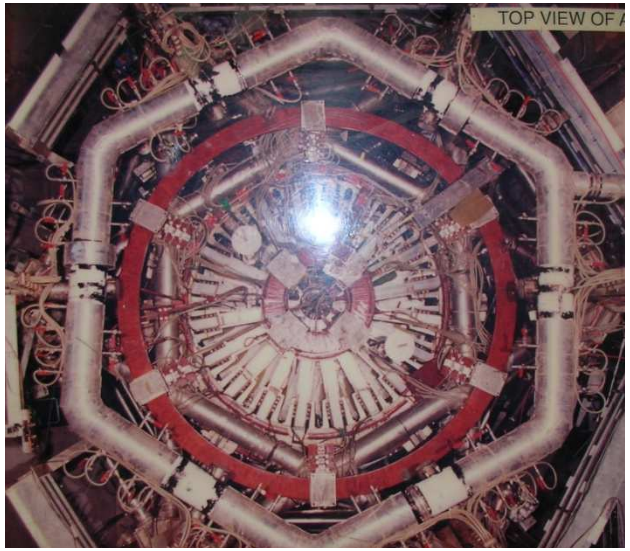
82.6GHz ECRH System

42GHz ECRH system

ECRH in Aditya

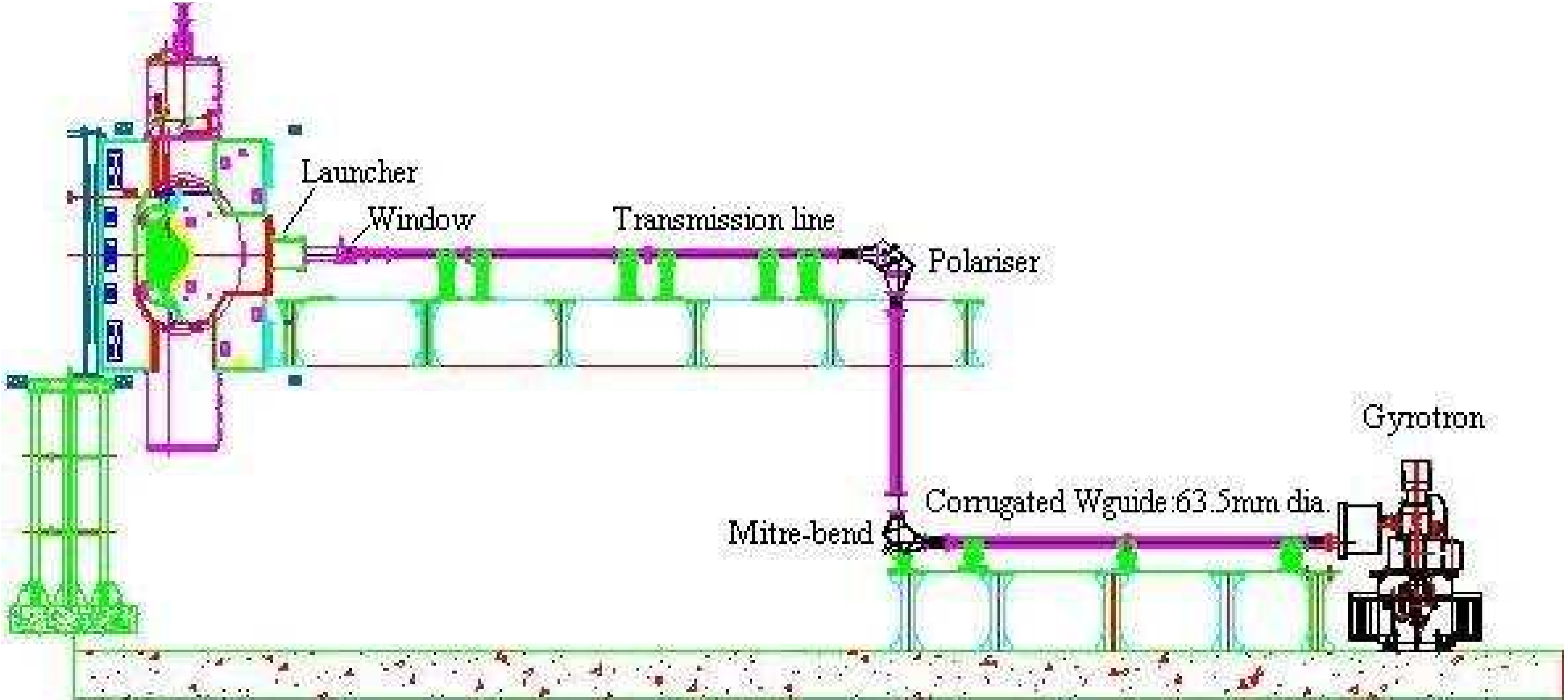
42GHz ECRH systems





ECRH Schematic in SST-1

- Frequency : 82.6GHz, Maximum Power : 200kW, Maximum Pulse duration : 1000s
- Fundamental O-mode and second harmonic X-mode launch from Low field side (Radial port)
- Transmission line consists of DC break, Corrugated waveguide , bends, polarizer and bellows
- Launcher – mirror based launcher used to focus the beam plasma



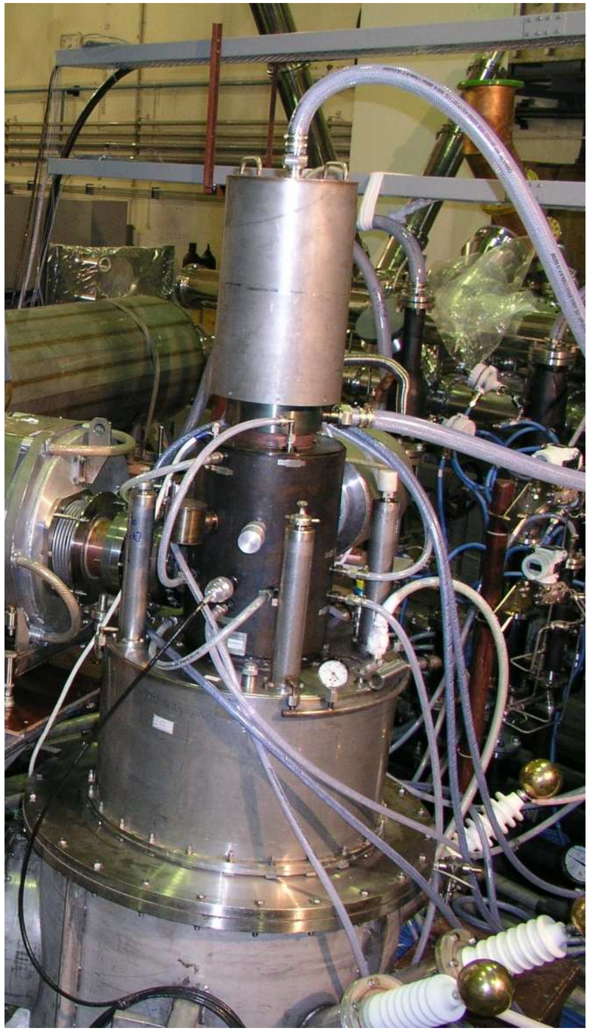
SST-1 ECRH system Gyrotron:

Microwave Source (Gyrotron):

- Depressed Collector type
- Frequency : 82.6±0.2GHz
- Power : 200 kW / CW
- Pulse duration : 1000s
- Duty Cycle : 17%
- Gyrotron output : lateral-horizontal
- Output mode : TEM_{00} – Gaussian beam
- Gyrotron output window : CVD diamond
- Magnet of gyrotron : cryo-cooled

Cooling of gyrotron:

- Collector, body, anode, ion pump and ballast load : cooled with DM water
- CVD Window : CC-15 mixed with DM water



Subsystems of Gyrotron

Mechanical

Electrical

Magnet

Microwave

DAC

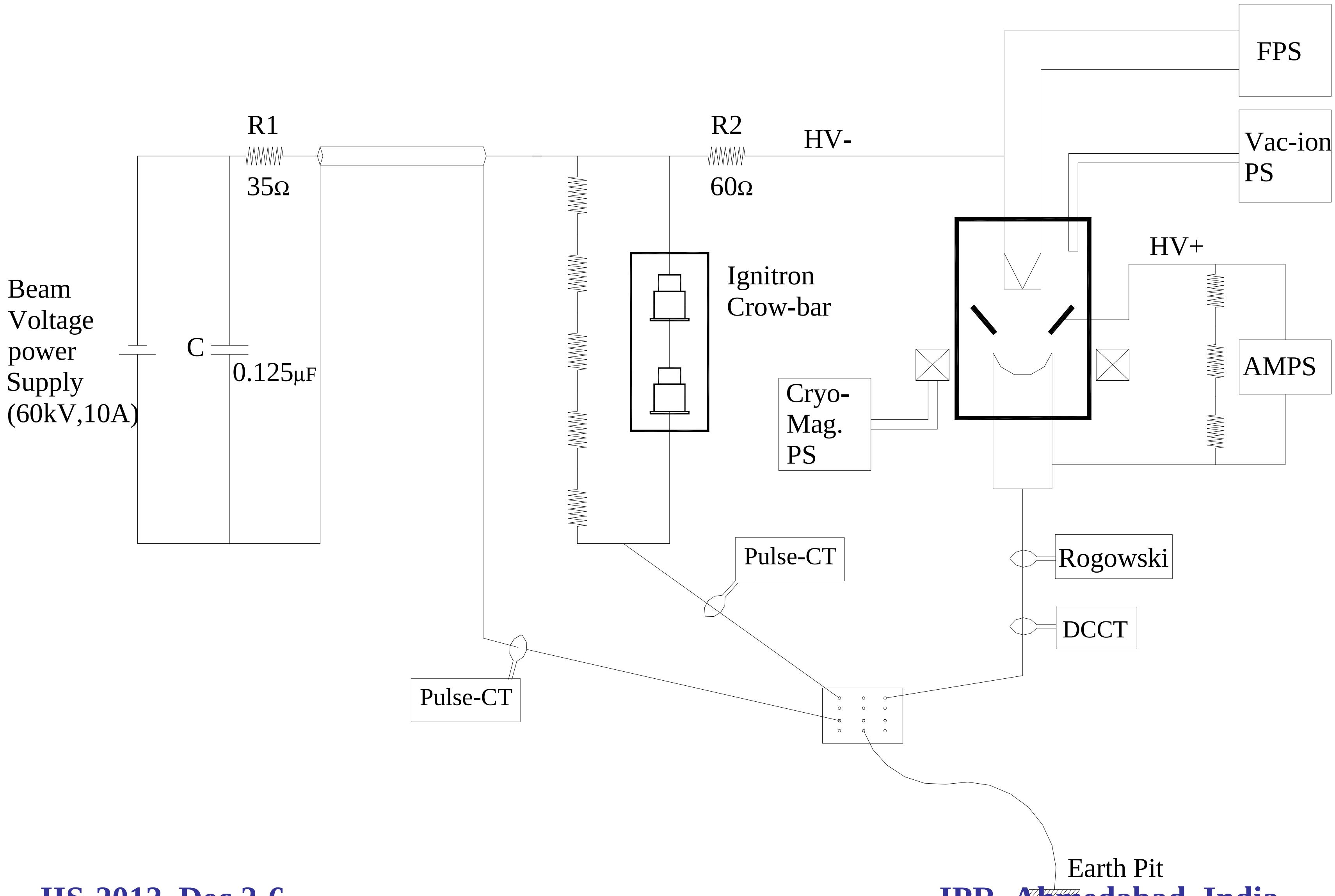
Interlocks

Instrumentation

Prior to high power test of Gyrotron..

- Electrical layout
- Mechanical layout
- Calibration of electrical instrument
- Calibration of microwave components
- Commissioning of Cooling system
- Test of DAC with dummy signal
- Test with real field signal
- HV connections to Gyrotron with professional wiring
- Dedicated HV ground close to Gyrotron

Electrical layout for Gyrotron



Interlocks

Fast Interlocks
< 10μs

Slow Interlocks
~ 100 ms

Action
Crowbar

Action
Software I/L

Fast Interlocks	Slow Interlocks
Arc	Cooling (all)
Beam voltage	Filament
Beam current	Magnet currents
Anode over current	Waveguide (vac or Pr.)
dI/dt	HVPS Over voltage ?
Body current	
Vac-ion current ?	

Most Critical for Gyrotron….

In an event of fault, the fault energy to the Gyrotron should not exceed its critical fault energy known as critical crater energy

Remove high voltage Fast enough i.e.

$< 10 \mu s$

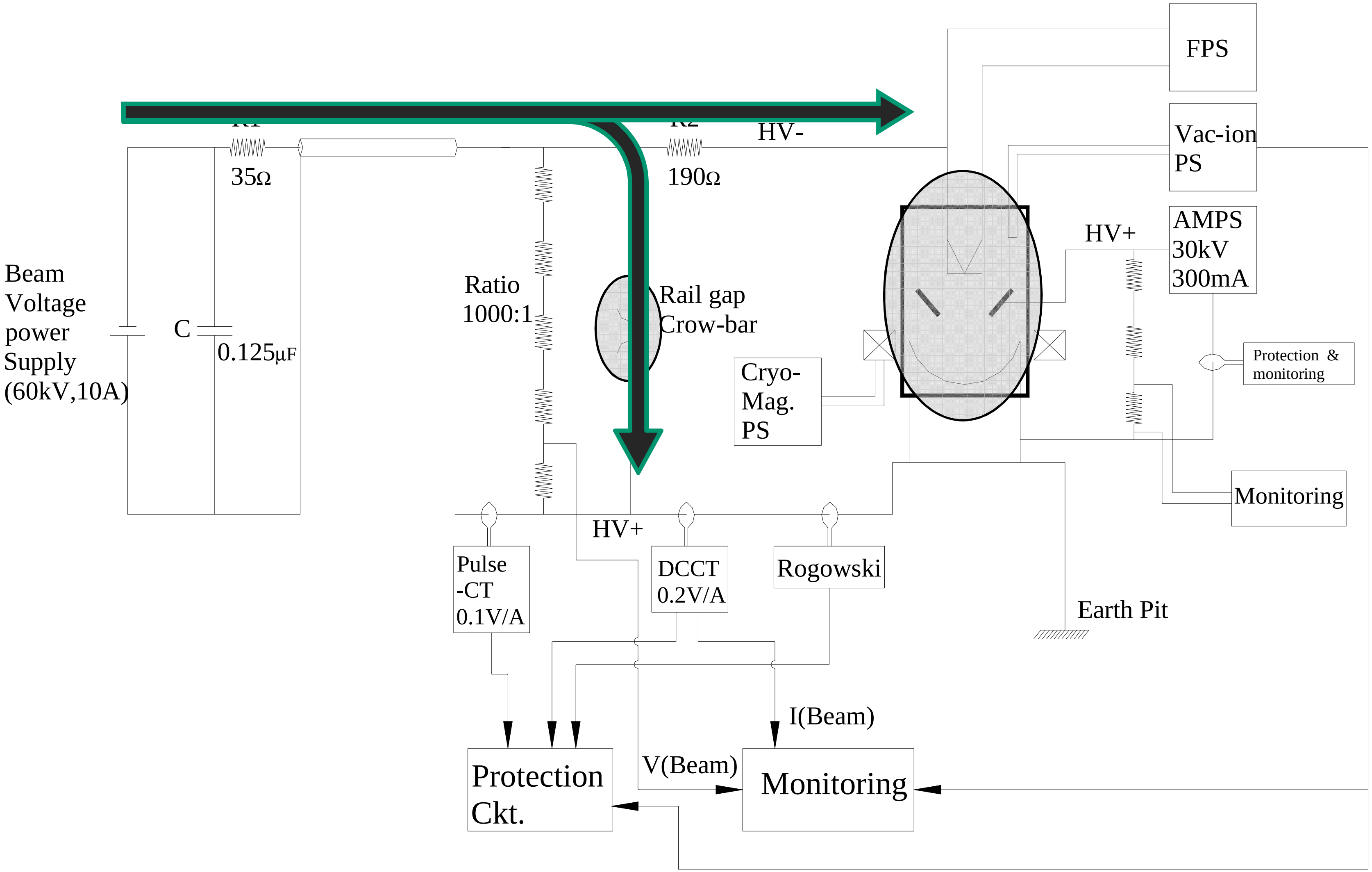
⇄

Demonstrate

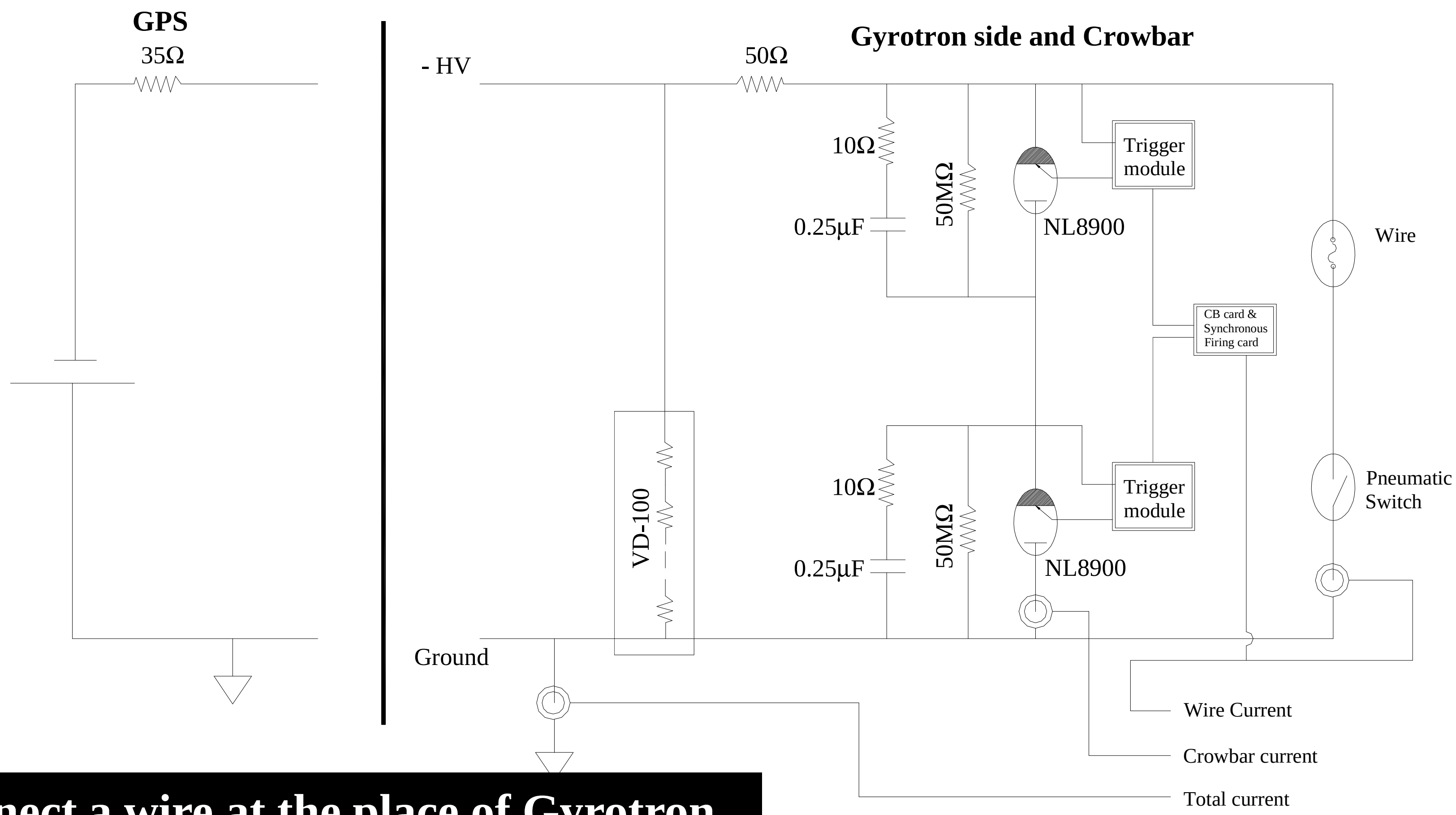
10-Joule

Wire test

Crowbar Protection



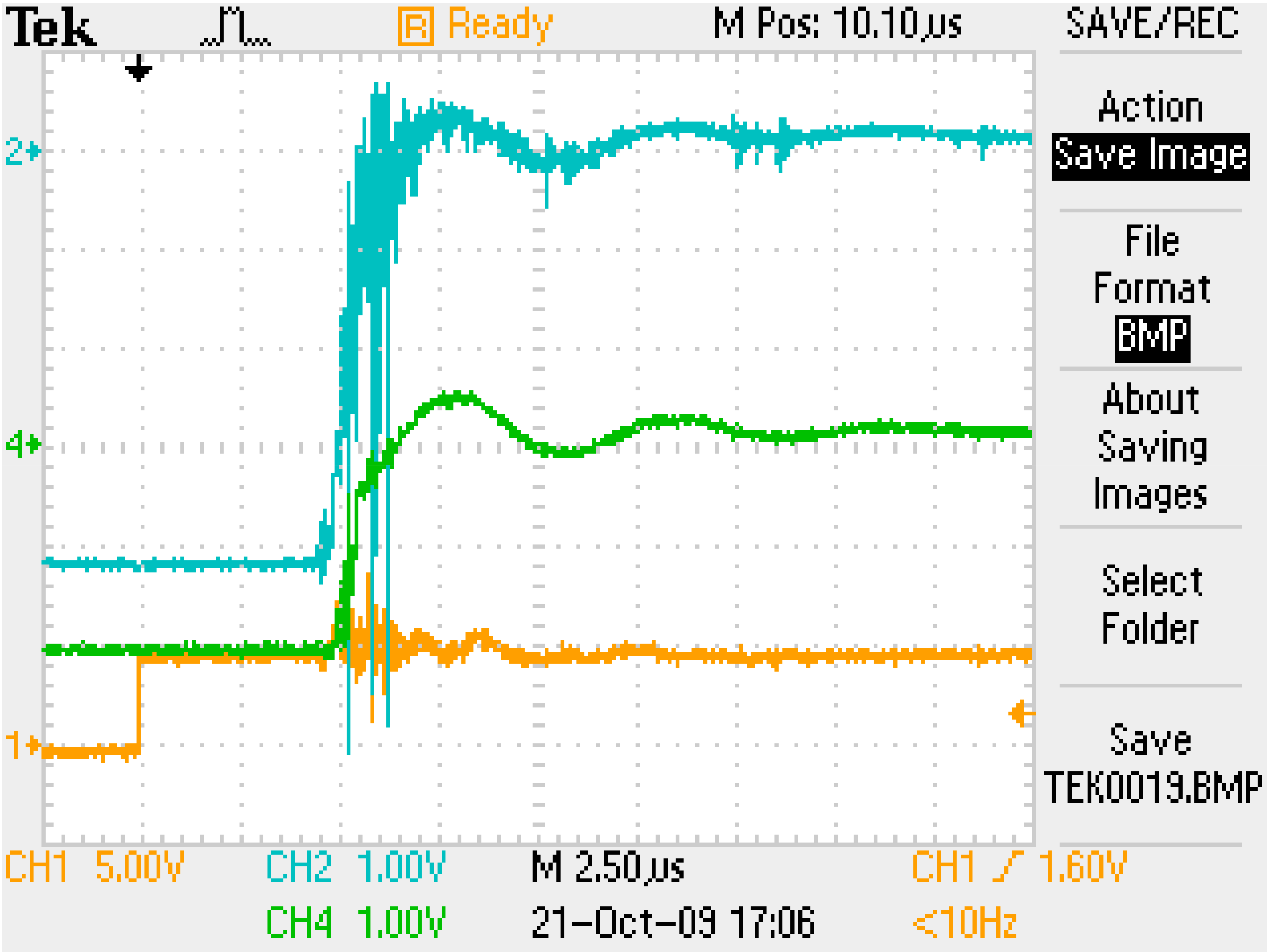
10-Joule wire test



- •Connect a wire at the place of Gyrotron
- •Generate manual fault
- •Detect the fault and trigger the crowbar
- •If wire safe, test successful

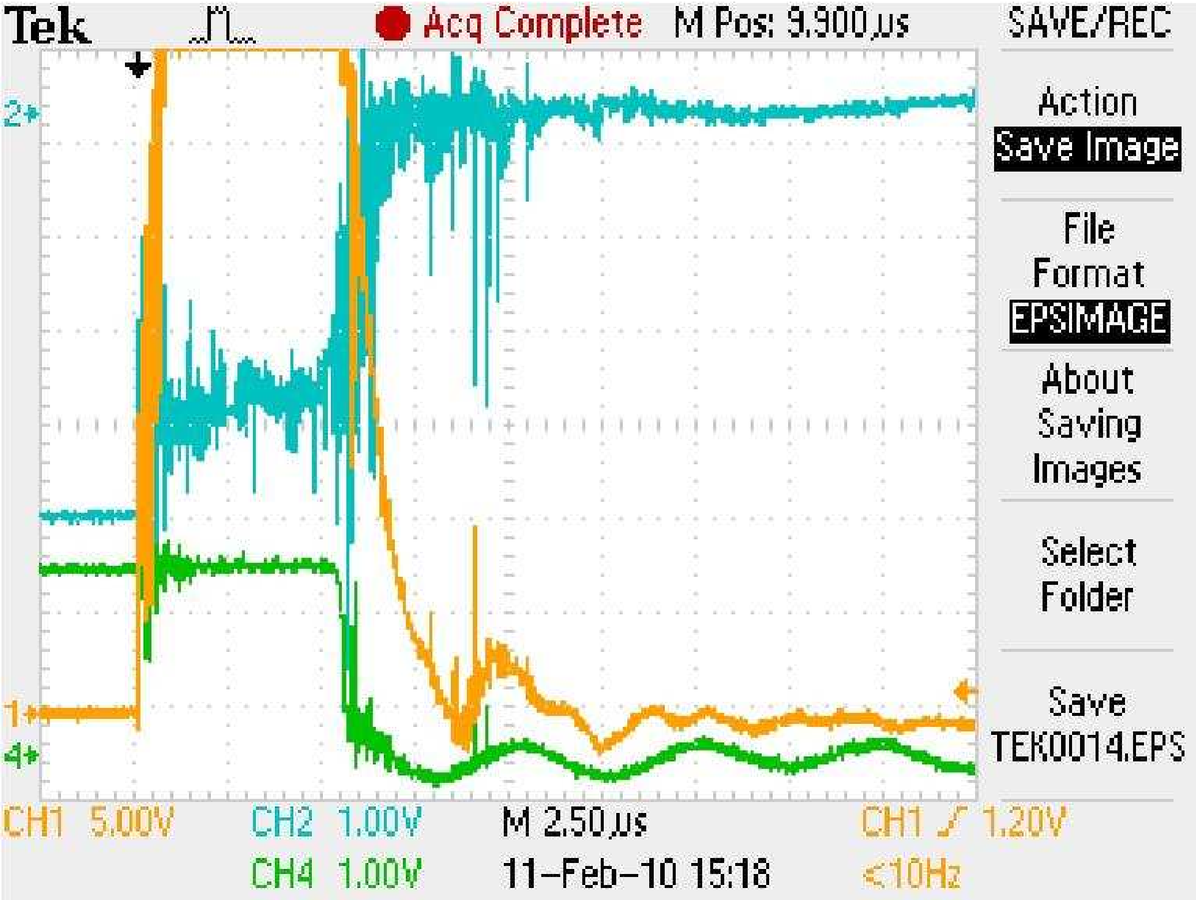
Ignitron crowbar system developed at IPR

HV switch OFF within 10μs

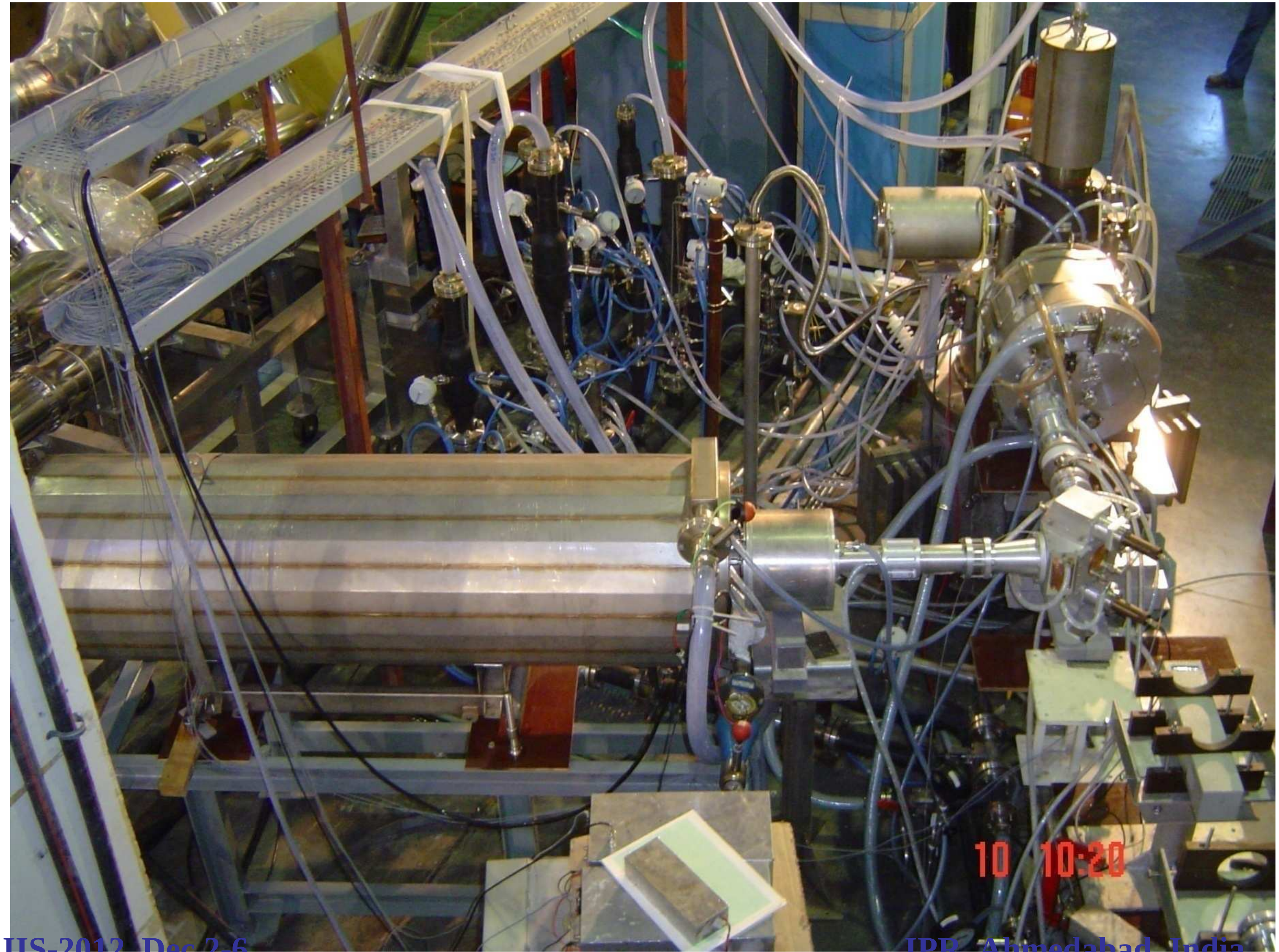


Integrated test of HVPS and AMPS

The integrated test to turn OFF HVPS (Voltage ~ - 43kV) and AMPS (Voltage ~ + 20kV) together is checked and it is found that both the power supplies switch OFF within 8 microseconds. During this test, 10Joule wire is used and it was safe during the HV shot.



Gyrotron test set-up with water Dummy load:



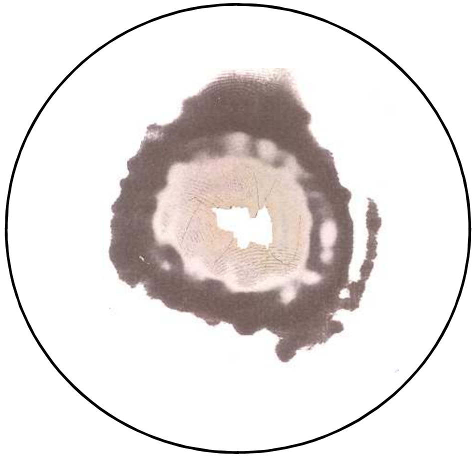
Gyrotron test results:
(Pulsed operation for burn pattern test)

Electrical parameters for burn-pattern test:

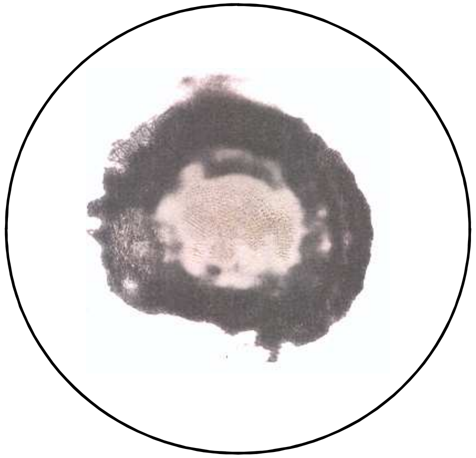
- Beam Voltage : -35kV

  Anode voltage : + 16kV

  Filament Voltage : ~ 30V
- Filament current : 18.5A
- Cryomagnet current : 45.33A
- Pulse duration: 30ms
- A : Paper at the output of MOU
- B : Paper at the output of 400mm waveguide at the output of MOU

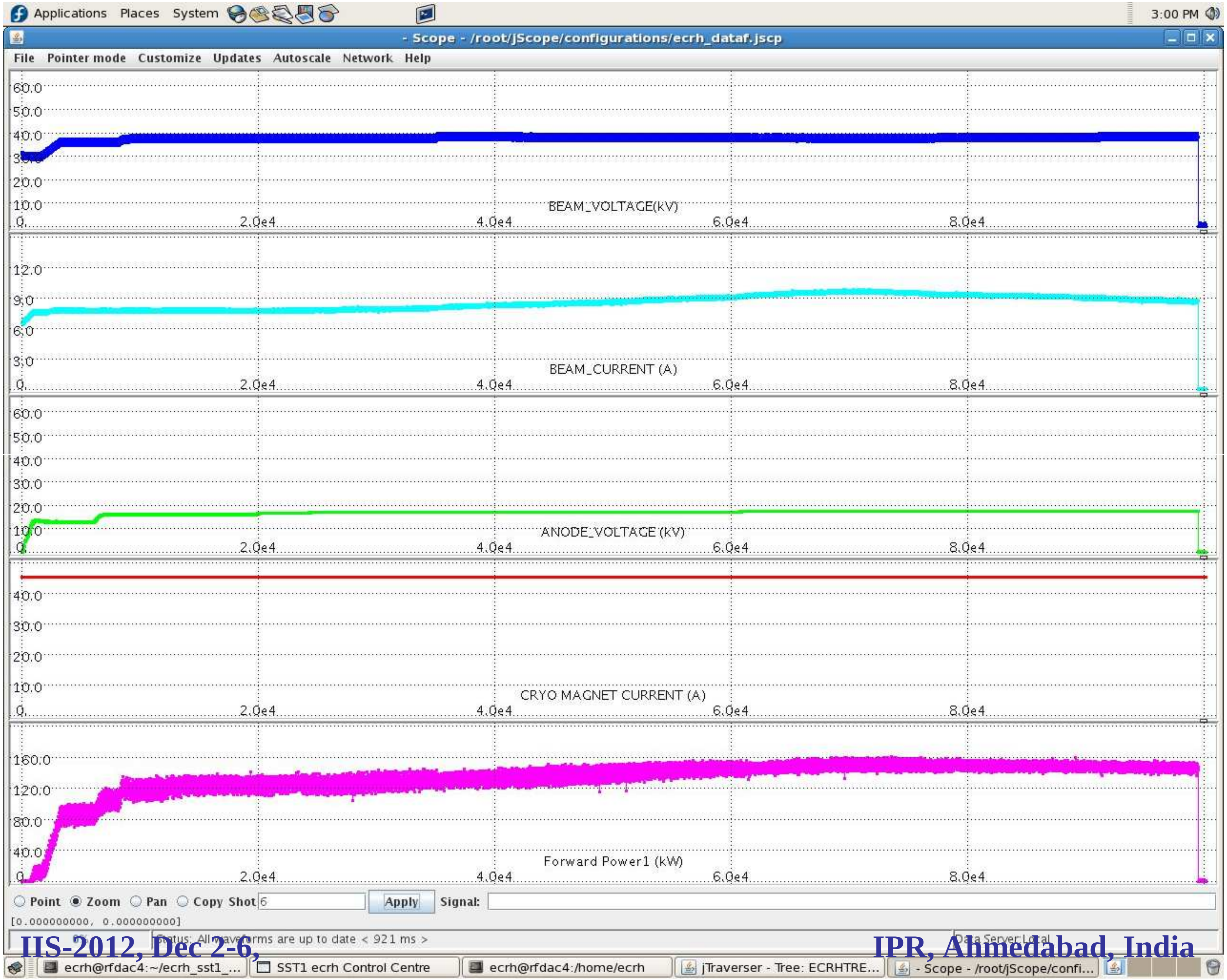


A

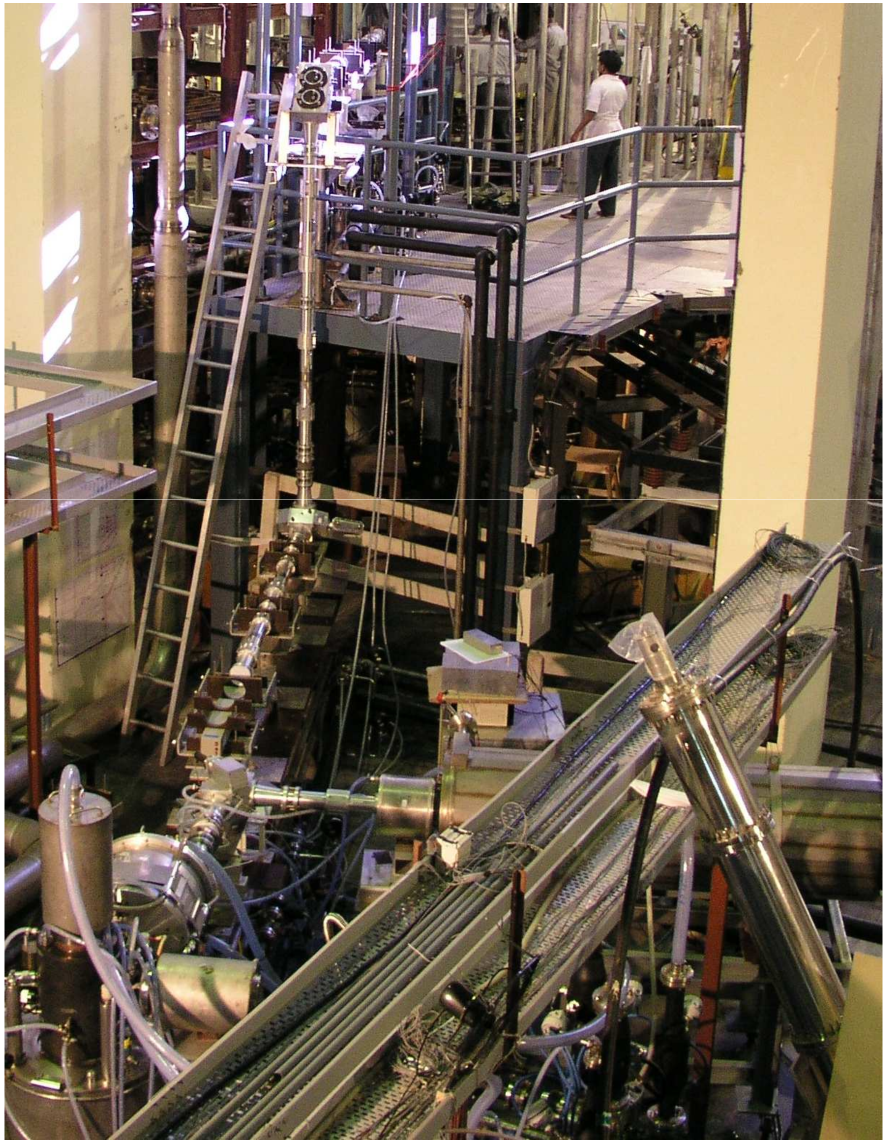


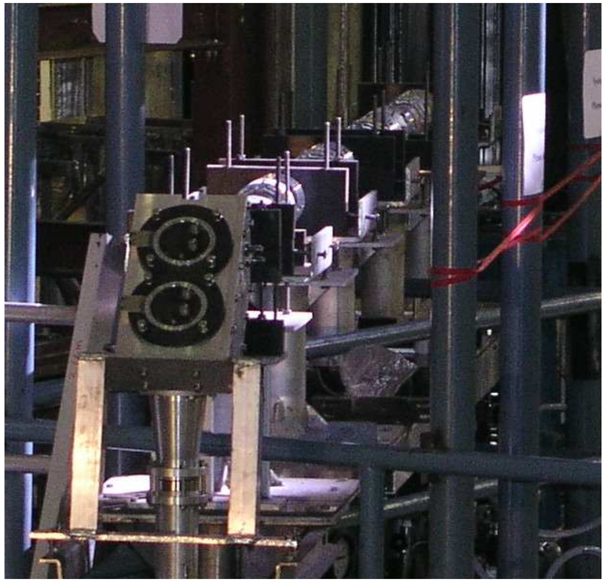
B

175 kW / 1000s Shot



Transmission line system and its high power test:





Burn Pattern at the exit of transmission line:

Beam Voltage : 35kV

Anode Voltage :16kV

Pulse duration : 30ms

Beam Voltage : 36kV

Anode Voltage :16kV

Pulse duration : 40ms

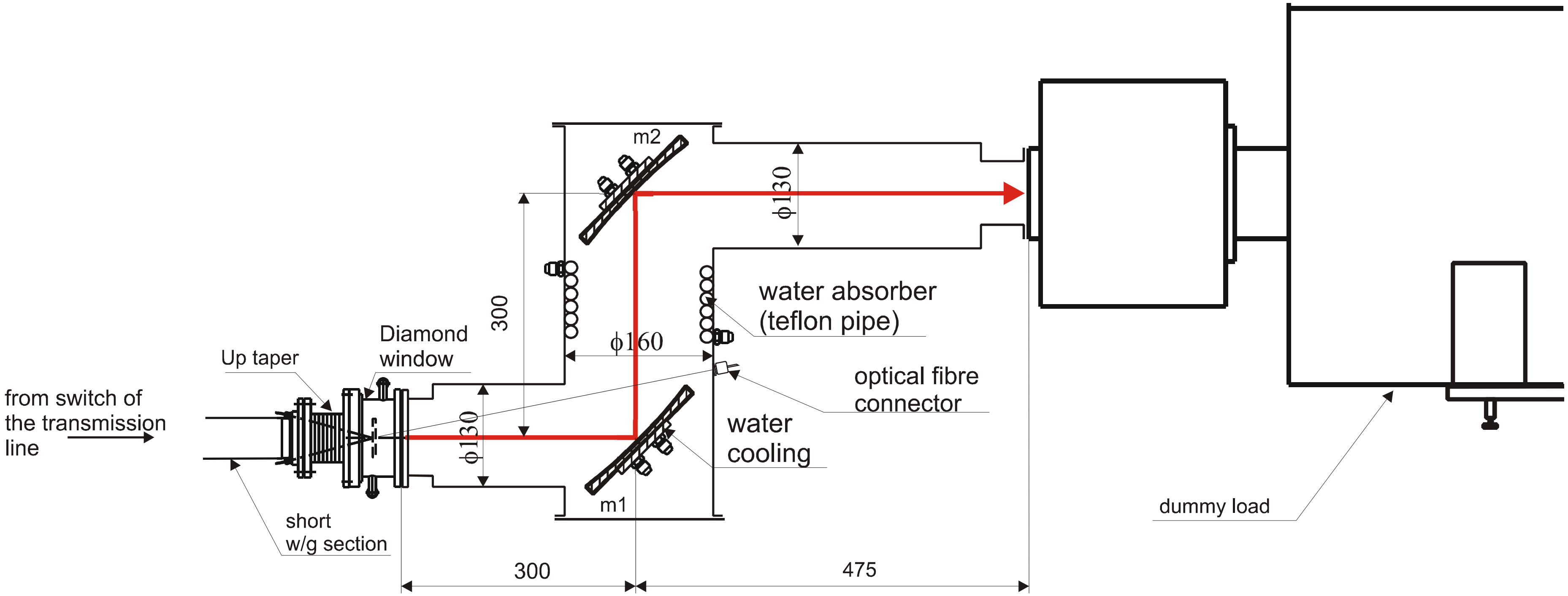
High power test of CVD diamond window

Schemes of CVD window test:

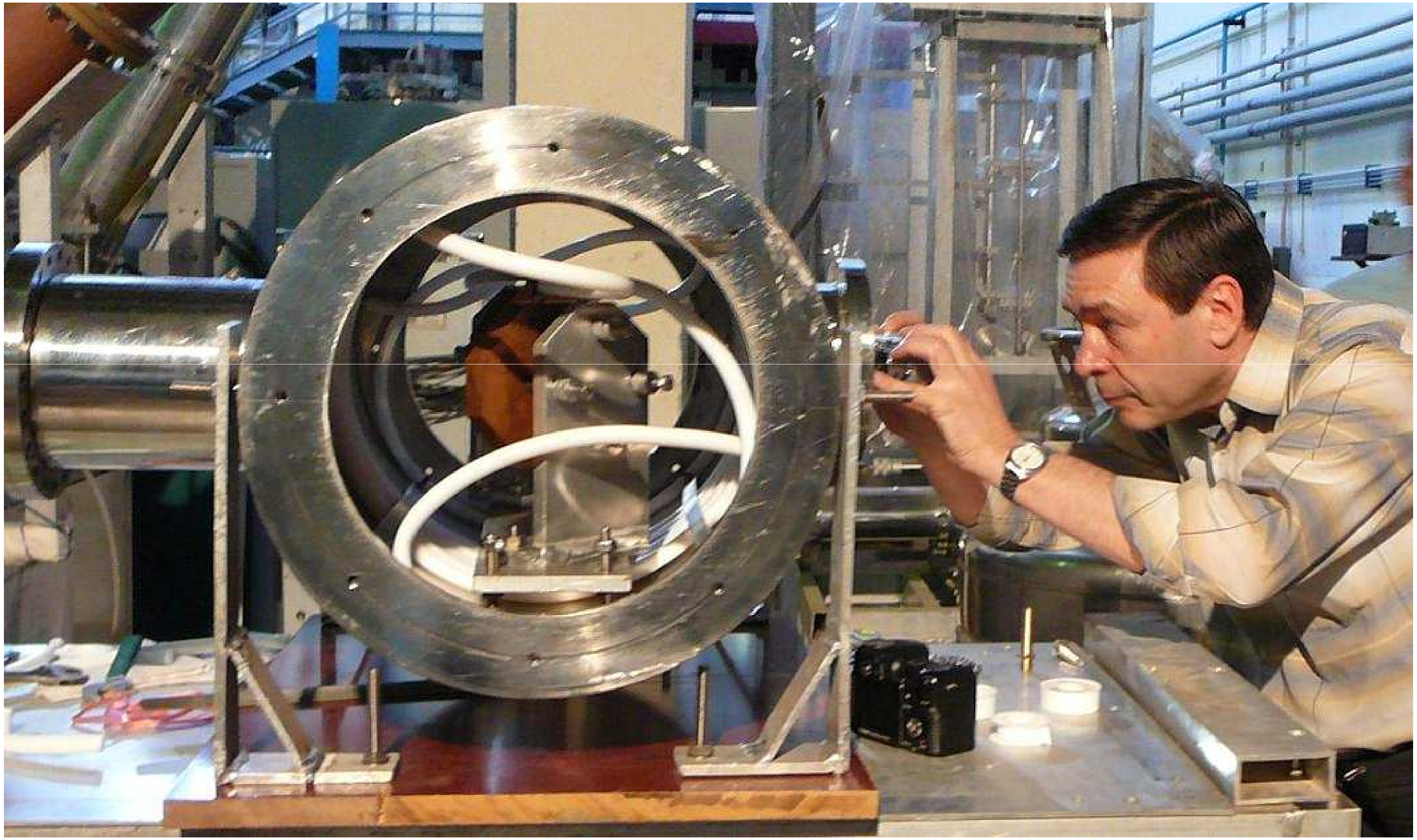
•On tokamak (×)

•Brick load (limitation 3 seconds only)

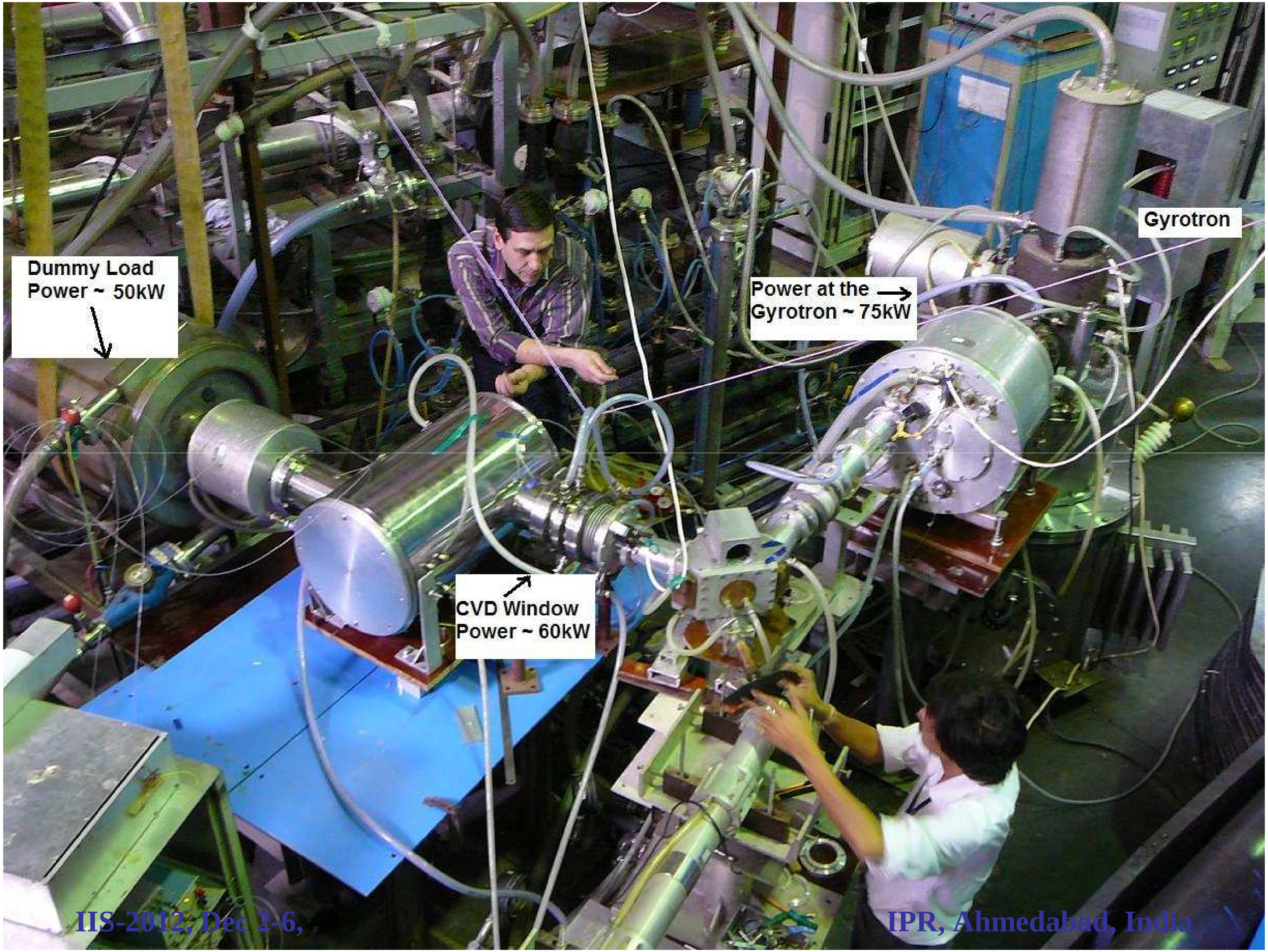
•On dummy load using a QO matching unit (Mirror-box) (√)



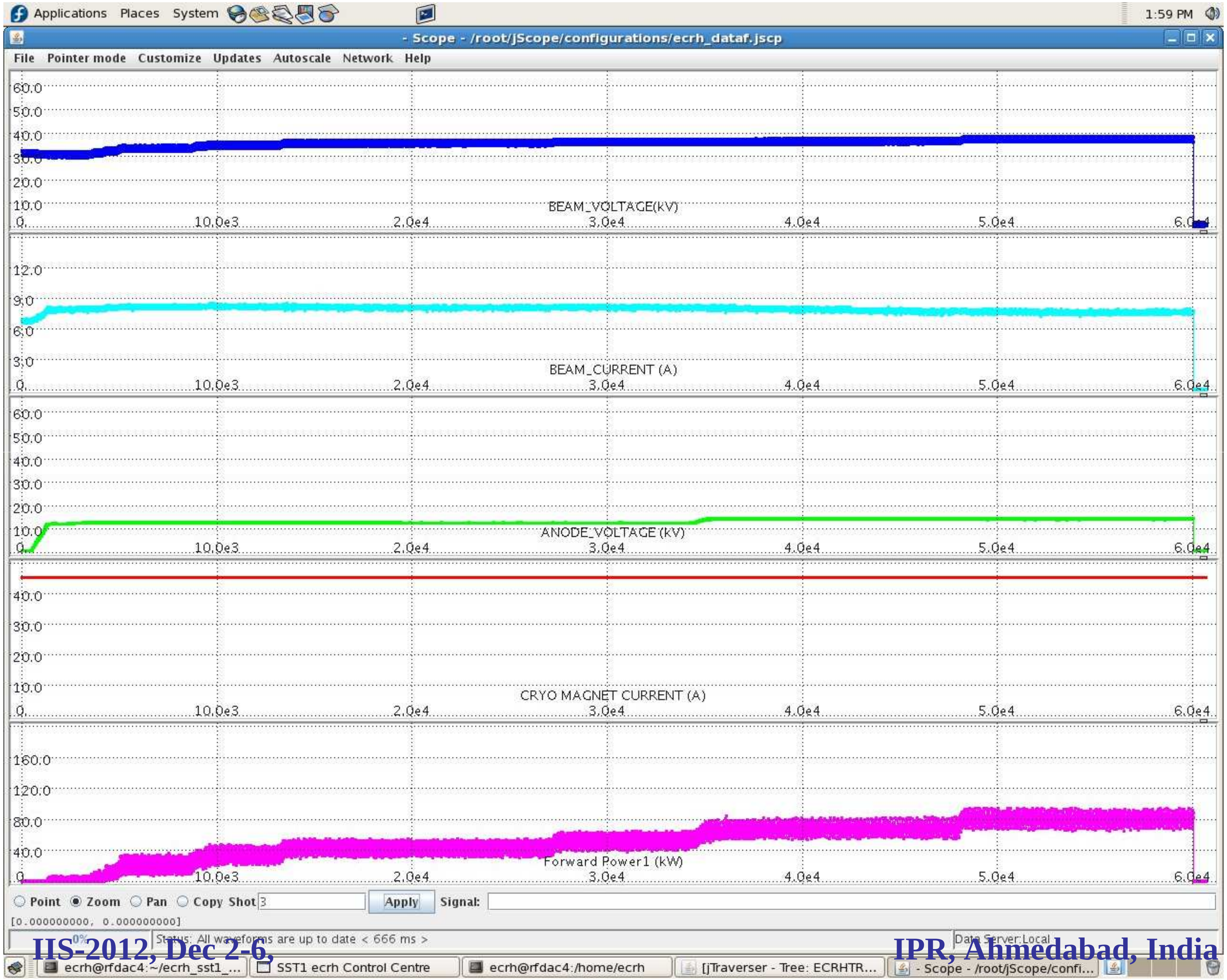
Mirror box inside view



High power test of CVD Diamond window



High power test of CVD window (Power @ the Gyrotron ~ 80kW for 10 minutes)



CVD window test:

1) UHV test: Vacuum 10-9 range is achieved with baking of ~150 deg. for ~ 24hrs

2) High power microwave test: Maximum power at the window: ~ 60kW / duration 10minutes in 1000s pulse as shot terminated manually without any problem

Looking the risk in operation with two diamond windows with a new approach of testing, the operation is limited to 60kW power. The test is restricted in power due to safety of CVD window and Gyrotron.

- **The similar CVD diamond window on the Gyrotron is already tested for 200kW/1000s. So window can be accepted at IPR.**

Present status 82.6GHz ECRH system is ready

160-180kW @ 82.6GHz

Second harmonic

breakdown @ 1.5T

Second harmonic ECRH breakdown in SST-1

Ionization growth rate $\beta = P^{1/2} a^{-1} \omega d_0$:

For SST1: P: 160kW, a: 0.2m, ω: *82.6GHz and* d_0: *63.5mm*

For DIIID-1 (P: 250kW, a: 0.65m, ω: *110GHz and* d_0: *60mm)*

$\beta^{SST1} / \beta^{DIIID-1} \sim 2$

For ITER (parameters as mentioned in ref [7]): P: 2400kW, a: 2.0m, ω: *120GHz and* d_0: *60mm*

$\beta^{SST1} / \beta^{ITER} \sim 1.8$

For T-10: P: 300kW, a: 0.3m, ω: *140GHz and* d_0: *63.5mm*

$\beta^{SST1} / \beta^{T-10} \sim 0.64$

For KSTAR: P: 450kW, a: 0.5m, ω: *84GHz and* d_0: *63.5mm*

$\beta^{SST1} / \beta^{KSTAR} \sim 1.46$

The study is being done, it is not yet concluded but 160kW power @ Second harmonic could be at threshold…..

42GHz ECRH system for SST-1 is proposed & now its in advance stage for commissioning on SST-1

42GHz / 500kW ECRH system for SST-1 and Aditya

For SST-1

Pre-ionization, start-up and heating at fundamental harmonic (1.5T operation)

In Aditya

Breakdown studies at second harmonic (0.75T)

ECRH systems at its application

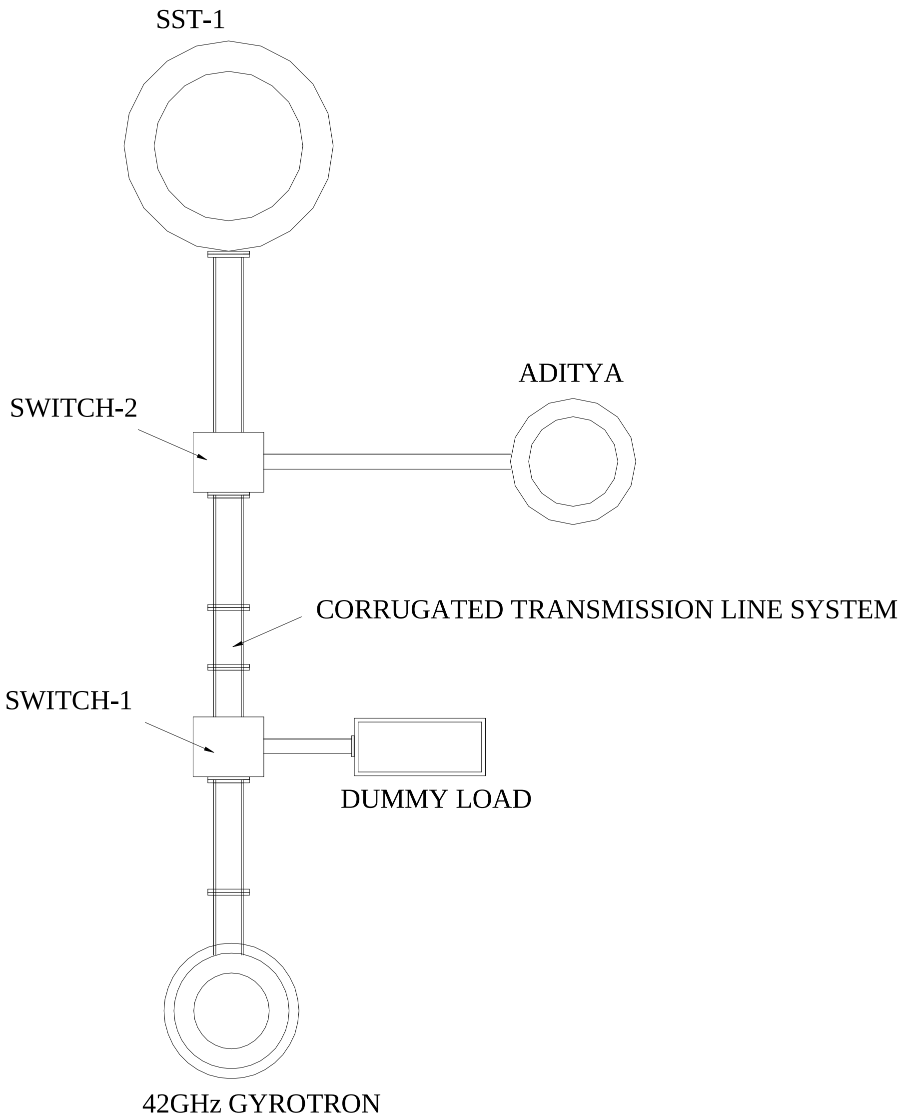
42GHz - 500kW-500ms

- Pre-ionization, heating @ second → ADITYA 0.75T
- Pre-ionization, heating @ Fundamental → SST-1 1.5T

82.6GHz - 200kW-CW

- Pre-ionization, heating @ second harmonic → SST-1 1.5T
- Pre-ionization, heating @ Fundamental → SST-1 3.0T

42GHz ECRH system for SST-1 and Aditya



Gyrotron:

Frequency : 42GHz

Power : 500kW

Pulse duration : 500ms

Gyrotron with internal mode converter

Gyrotron output : HE11 (Gaussian output)

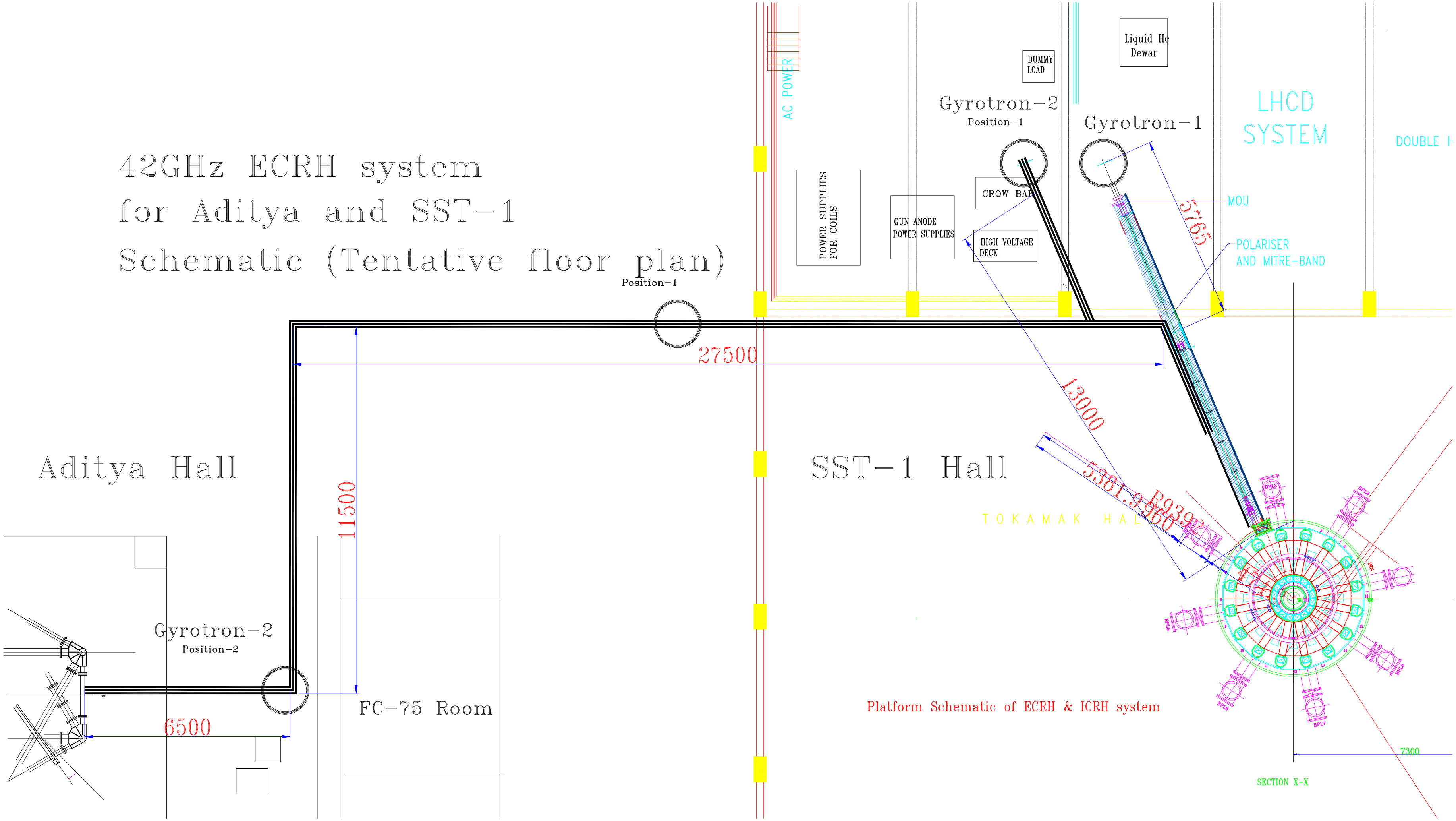
Depressed collector type Gyrotron,

Efficiency ~ better than 45%

Gyrotron with external MOU

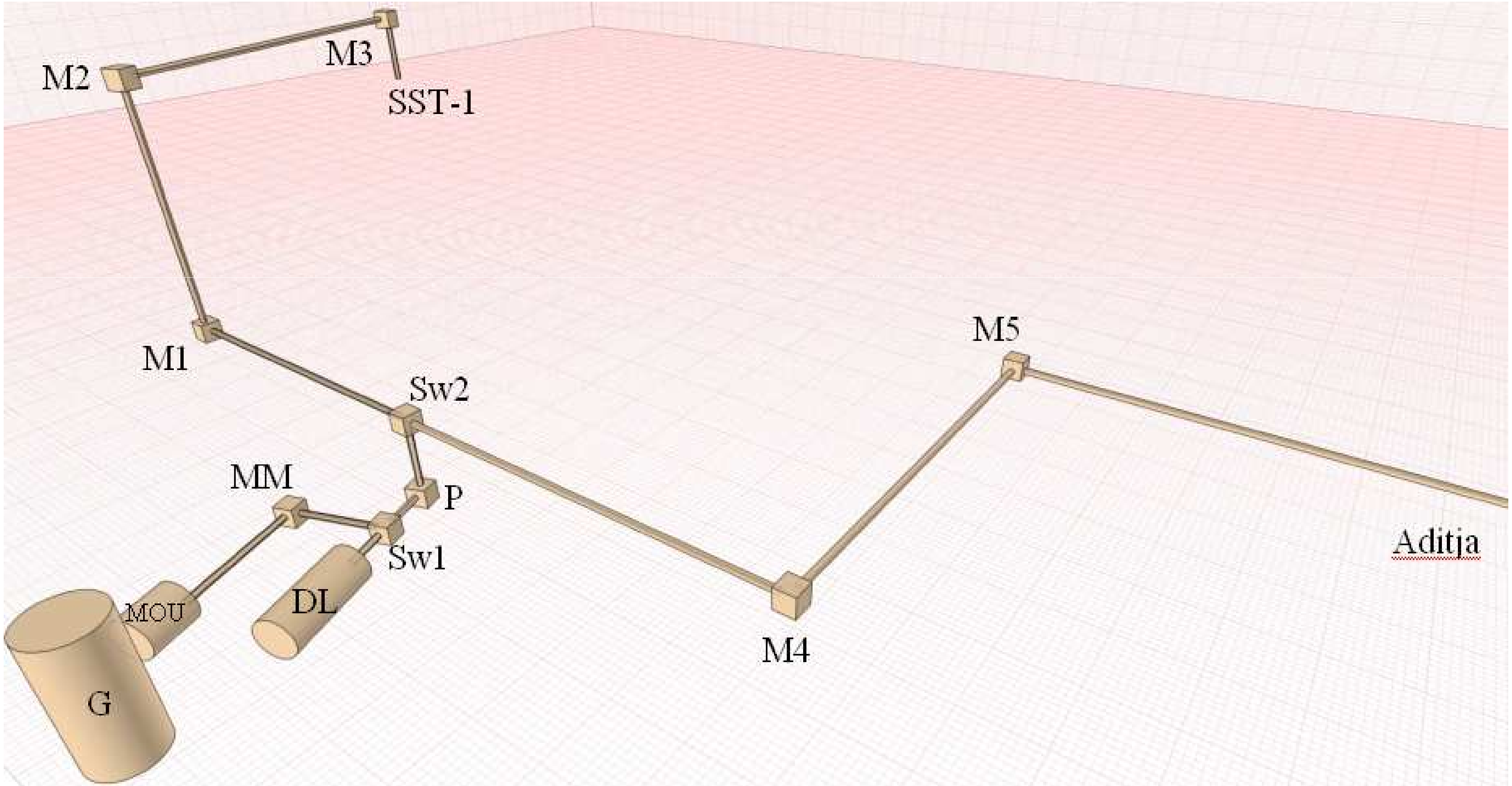
Calorimetric dummy load

Layout of 42GHz ECRH system in SST-1



Transmission line system for 42GHz / 500kW ECRH system for SST-1 and Aditya

Two switches, One polarizer, ordinary bends, bends with directional coupler, DC breaks, bellows and 75m corrugated waveguide

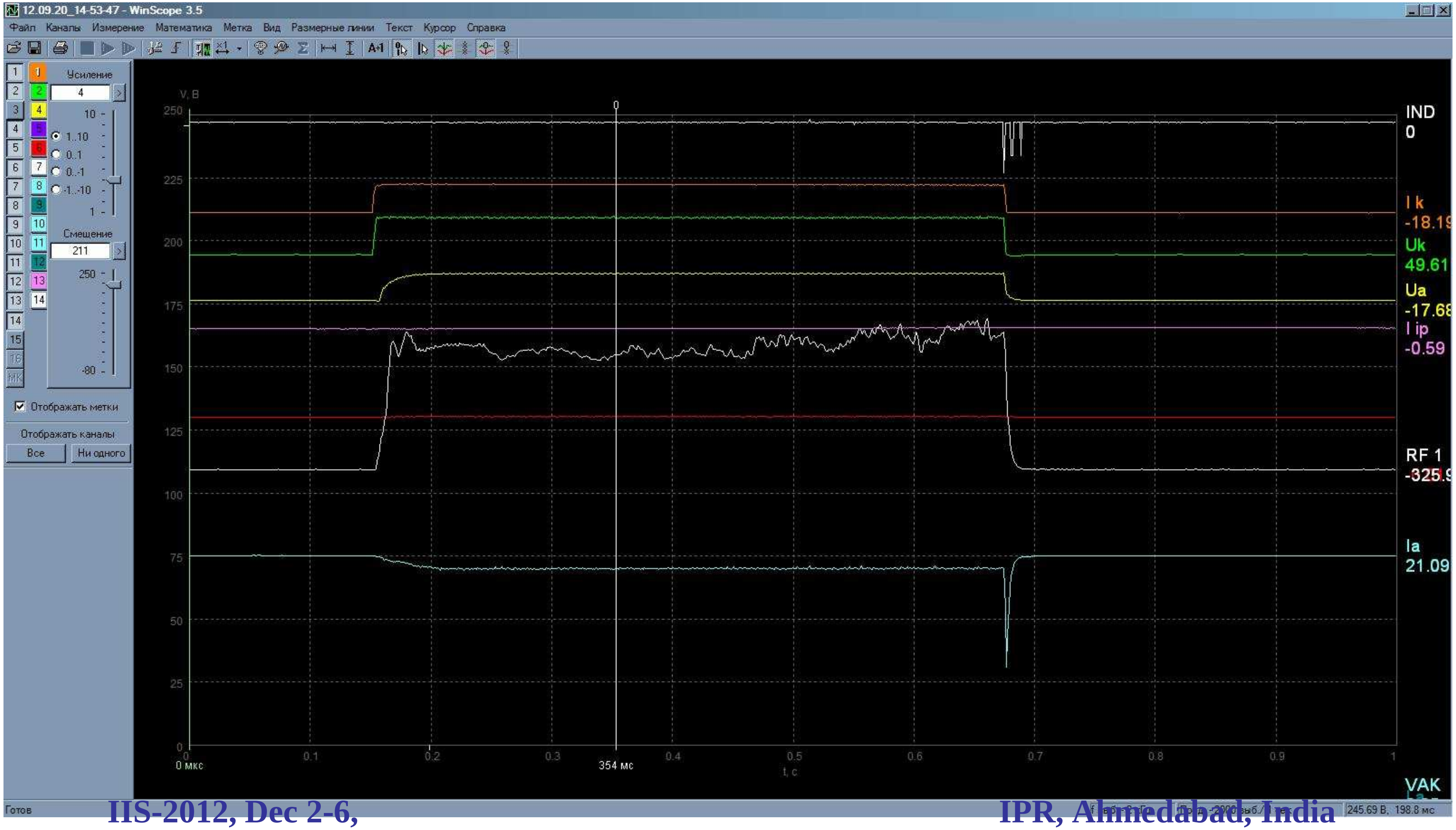


42GHz / 500kW ECRH system for SST-1 and Aditya

The entire system has been tested at M/s. Gycon in Russia for 500kW-500ms the efficiency is more than 50%

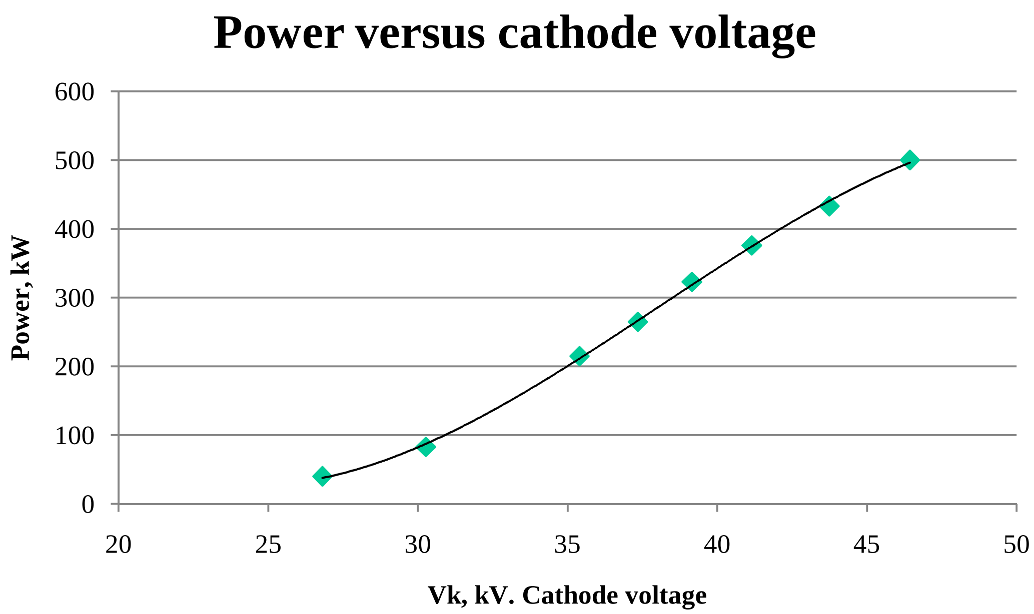
High power test of 42GHz Gyrotron

Power : 500kW, duration : 500ms



High power test of 42GHz Gyrotron

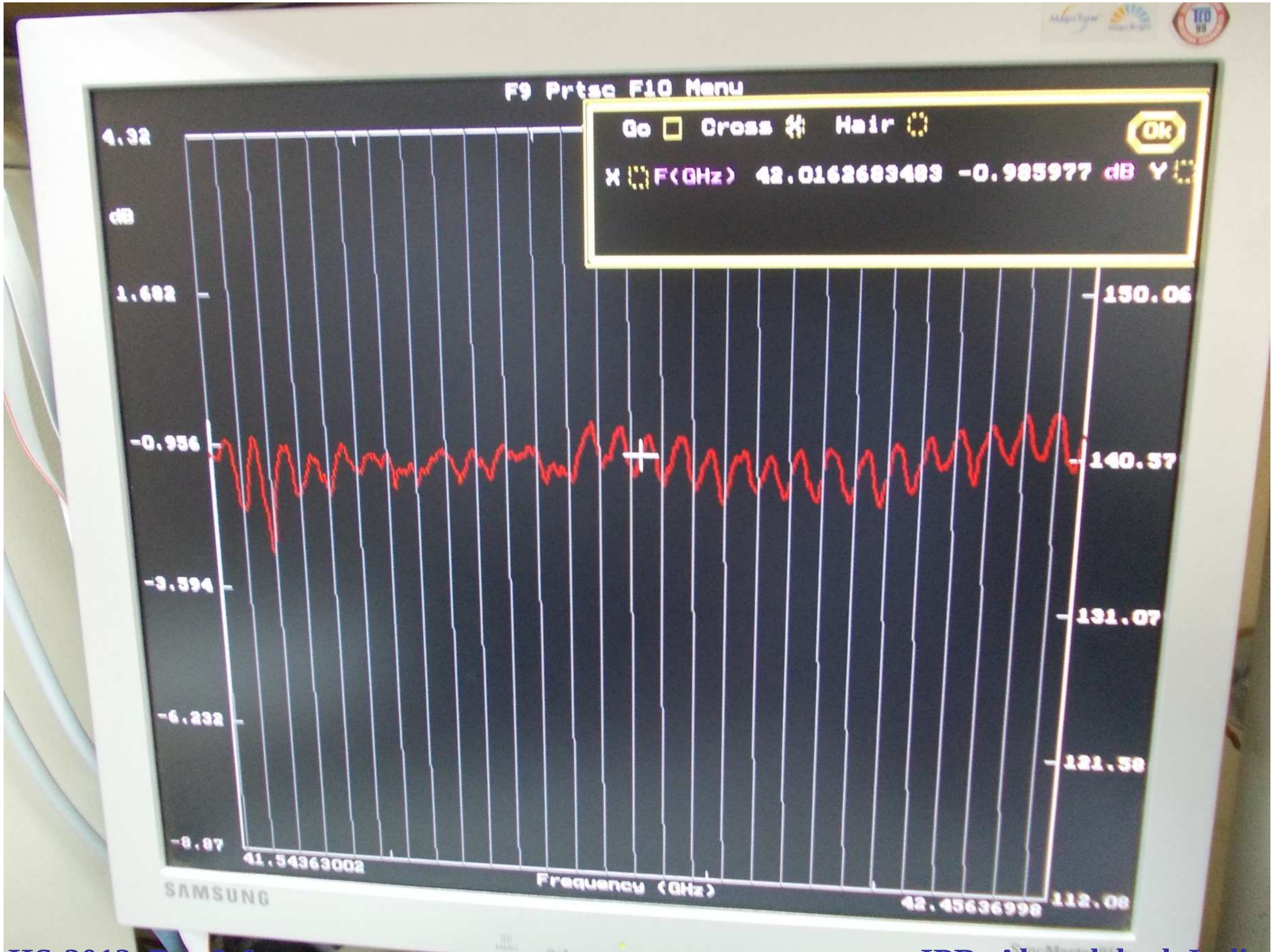
Power : 500kW, duration : 500ms



Frequency measurement of Gyrotron

Transmission line test

Transmission line test



High power test of windows

42GHz ECRH system on SST-1

Tested at factory for its performance

Planned for commissioning of system on SST-1 & Aditya soon

Launcher for ECRH in SST-1

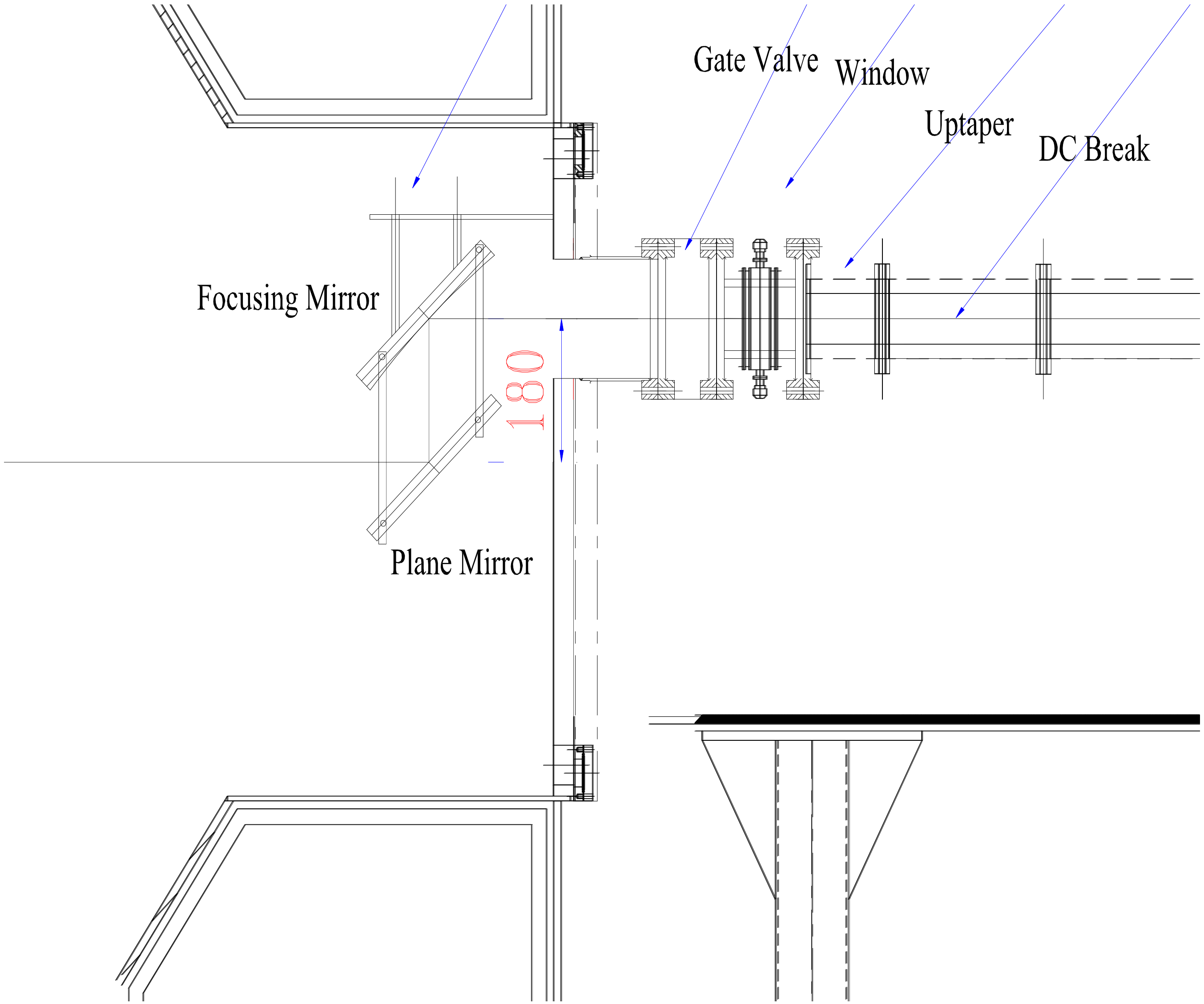
ECRH is allotted for single port

Launcher is designed such that to accommodate both the systems

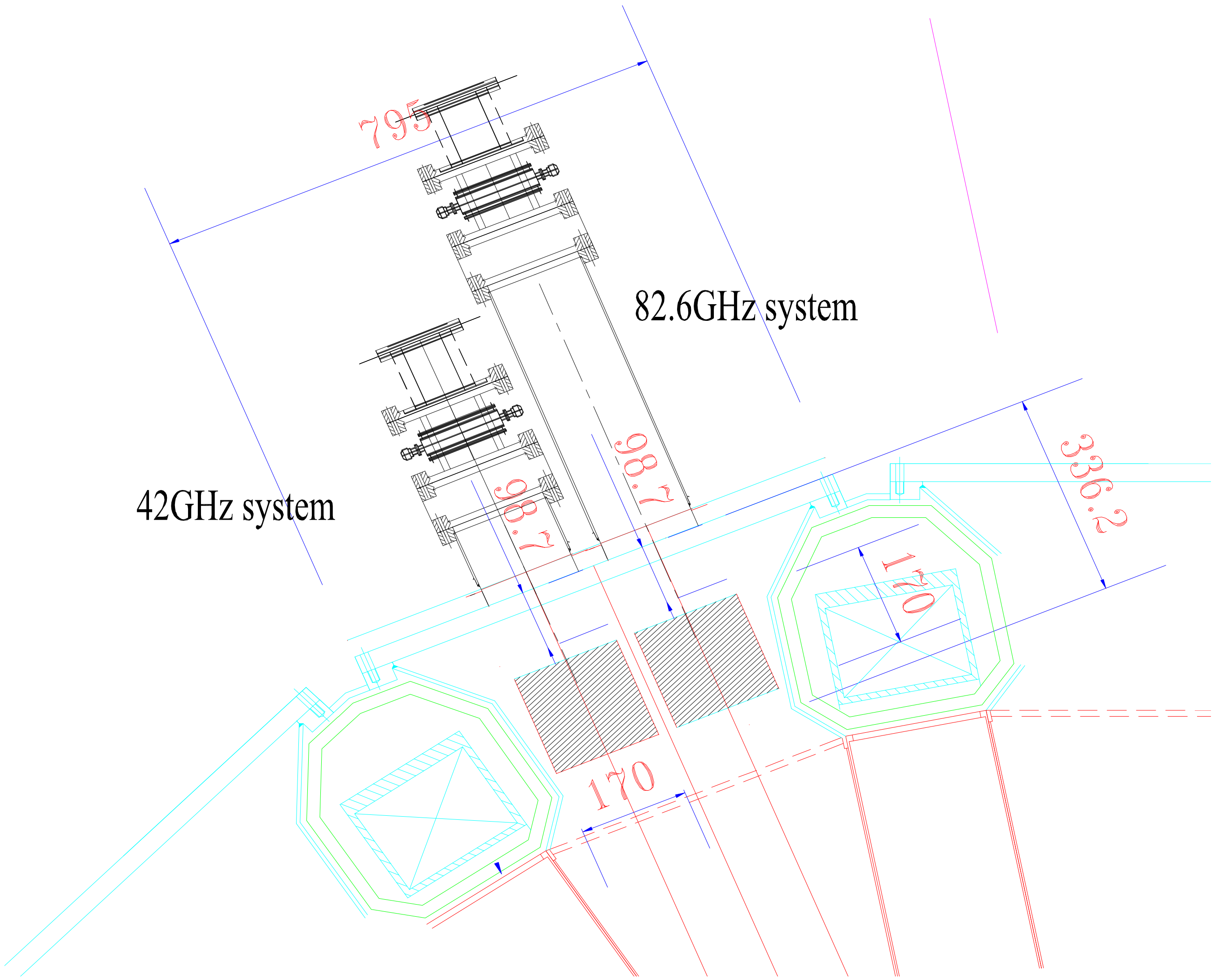
82.6GHz and 42GHz system would be connected to same port

One focusing mirror and one plane mirror combination is used for both the systems

Launcher for ECRH in SST-1



Launcher for ECRH in SST-1



Launcher for ECRH in SST-1

42GHz launcher:

Mirror Size: 170mm x 240mm

Mirror focal length: 353mm

Beam size (1/e radius) at Plasma center: 35mm

82.6 GHz launcher:

Mirror Size: 140mm x 200mm

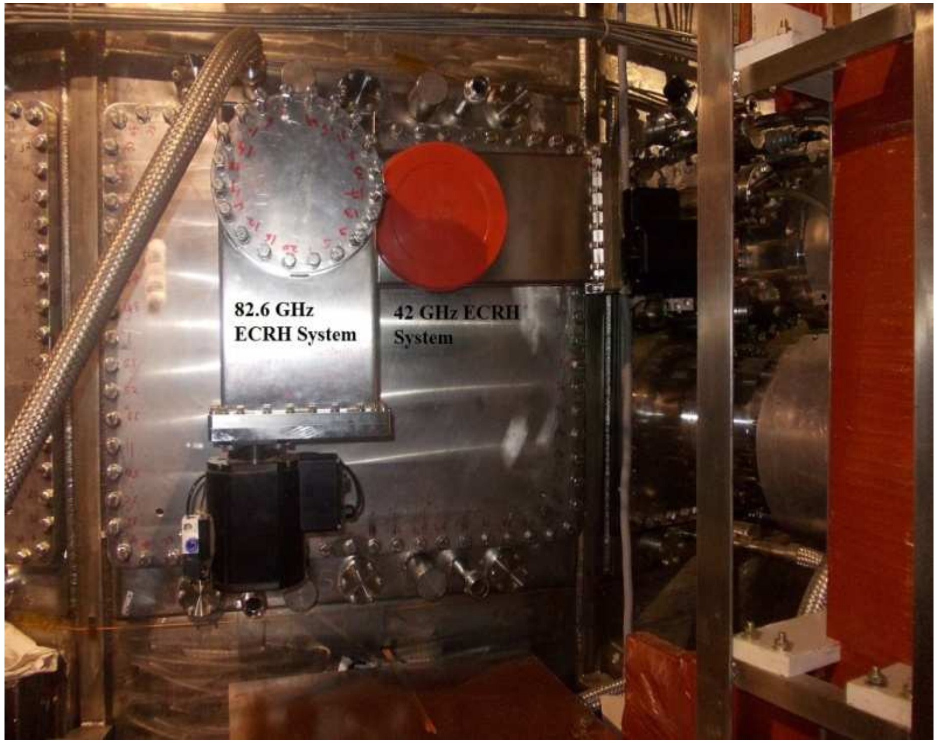
Mirror focal length: 481mm

Beam size at Plasma center: 20mm

Low power test of launcher

-50	0.2
-45	0.4
-40	1.1
-35	2.35
-30	4.5
-25	7.4
-20	10
-15	13.5
-10	17.6
-5	19.4
0	21
5	19
10	16.6
15	12.5
20	8.3
25	4.7
30	2.5
35	1
40	0.3
45	0.1
50	0.1

Launcher for ECRH in SST-1



Launcher for ECRH in SST-1

Advance launcher with further optimized mirrors and feasibility to steer the beam is under design

Future Plan for ECRH

Upgrade the ECRH system with power and frequency

Advance launcher capable to steer the beam in plasma

Summary

- In SST-1 and Aditya ECRH would be launched from Low field side
- In SST-1 82.6 and 42GHz ECRH system would be launched to carry out ECRH experiments at fundamental and at second harmonic
- *The 82.6GHz Gyrotron has been tested for pulsed condition using RHVPS.*
- In Aditya 42GHz ECRH system would be used for second harmonic ECRH experiments at 0.75T operation
- The 82.6GHz ECRH system is ready for SST-1 tokamak
- The 42GHz ECRH system has been tested at factory and scheduled to commission on tokamak SST-1 and Aditya soon.

Thank You

Visit Again